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The objective of this TOP is to describe various methods and instrumentation used in the initial validation of accelerometers to be used in both Ballistic Shock testing and crew/vehicle survivability Live Fire Test and Evaluation.

15. SUBJECT TERMS
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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 01-1-070 5 June 2017
DTIC AD No.

INITIAL VALIDATION OF BALLISTIC SHOCK ACCELEROMETERS

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1. SCOPE.

The objective of this Test Operations Procedure (TOP) is to describe various methods and instrumentation used in the initial validation of accelerometers to be used in both Ballistic Shock testing and crew/vehicle survivability Live Fire Test and Evaluation (LFT&E).

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

a. Live fire test range requirements.

(1) A live fire test range will be needed for the culmination of testing which includes explosives testing with a tuned reaction mass.

(2) The range must have the capability of firing non-cased explosives up to 50 pounds (lb) of C4 equivalent.

(3) The ability to record high speed photography directly overhead of test setup is required for reference instrumentation.

(4) Approved laser clearance and authorized safety paperwork for use of Laser Doppler Vibrometer (LDV) and/or Photon Doppler Velocimeter (PDV) systems may be required.

(5) Test rig jump height (up to 20 feet (ft)) should be considered when choosing a range.

b. Ballistic shock simulation requirements.

(1) An indoor facility with test apparatus capable of providing average ballistic shock or greater, in accordance with Military Standard (MIL-STD)-810G CN1[1**] (Method 522.2), is required.

(2) Access to an air compressor for operation of a gas gun.

(3) The capability for reference measurements via a LDV.

2.2 Instrumentation.

a. High-*g* Micro Electrical Mechanical System (MEMS) accelerometer.

(1) The MEMS accelerometer is the focus of the validation techniques provided and is not used to cross validate other accelerometers.

** Superscript numbers correspond to Appendix D, References.

(2) Piezoelectric (PE) accelerometers are not included in this TOP.

b. Laser Doppler Vibrometer.

(1) The LDV is a non-contact velocity and/or displacement transducer, which is used to measure the magnitude and frequency content of micron-to-large sized parts[2].

(2) LDVs focus a laser beam on the structure to be tested. The structure scatters or reflects light from the laser beam and the Doppler frequency shift, or phase shift, of the backscattered light is demodulated to measure the component of velocity / displacement, which lies parallel to the axis of this laser beam.

(3) Laser Vibrometry is a very sensitive optical technique capable of measuring sub-picometer displacements from near direct current (DC) to several Megahertz (MHz). In addition to their wide frequency range, LDVs have dynamic range not matched by other sensors. This enables measurements that cannot be accomplished by other optical techniques.

(4) The LDV must have a frequency response of at least 1.5 MHz with a maximum velocity range of at least 10 meters/second.

c. Digital volt meter (DVM).

d. Power supply.

2.3 Data Acquisition System and Equipment.

Data acquisition instrumentation must meet or exceed the recording instrumentation specifications provided in MIL-STD-810G CN1, Method 522.2 Ballistic Shock, Section 4.4.2. These specifications are provided in Appendix A.

a. Oscilloscope.

(1) For some portions of testing an oscilloscope capable of measuring up to 100 mega samples per second with at least 12 bit resolution is required.

(2) Must be able to provide usable data output for post-test manipulation.

b. Versatile Information Systems Integrated On-Line (VISION) High-Speed Digitizer (VHSD) data acquisition system. A detailed description of the VHSD is found in the U.S. Army Aberdeen Test Center (ATC) Internal Operating Procedure (IOP) MISC TB10002 BTSX Hardware Overview[3], ATC IOP MISC TB 10004 BTSX Calibration[4], and ATC IOP MISC TB10005 BTSX Signal Conditioner/Digitizer Add-On Module Procedure[5].

3. BACKGROUND.

3.1 Ballistic Shock Definition.

a. Method 522.2 of MIL-STD-810G CN1 defines ballistic shock as “a high-level shock that generally results from the impact of projectiles or ordnance on armored combat vehicles”. Typical engagements of interest also include Kinetic Energy projectiles, land mines, and improvised explosive devices. For the purposes of this TOP, ballistic shock is generally referred to as the sudden high-rate loading resulting from under body blast (UBB) testing designed to assess the crew-survivability of military vehicles. Historical testing conducted in both areas have proven the relative similarities between the two environments, and they will be used interchangeably herein.

b. Live-fire and other ground tests conducted with modern instrumentation have proven that the damage potential of ballistic shock is not only to the test item, but also to the instrumentation used to quantify the severity of the event as well. One of the primary interests of ballistic shock studies is to ensure that armored vehicles and their occupants survive the encounter while retaining their mission capabilities. To help assess this, the instrumentation used to quantify the survivability of the event must itself survive the test and provide accurate data.

c. One of the primary means of collecting ballistic shock data is through the use of accelerometers. Capturing valid acceleration data in this environment can be particularly challenging. Many preparations must be taken to ensure the highest likelihood of obtaining a valid record. For example, data acquisition systems must be placed several hundred feet from the test pad in a hardened bomb proof, and instrumentation cabling must be protected from fragmentation with underground troughs, steel beams, and flexible ballistic wrapping. Care must be taken to ensure that instrumentation cabling isn’t susceptible to triboelectric effects resulting from blast overpressure exposure. Proper strain relief techniques must be used on accelerometer cabling to ensure cable “whip” is reduced as much as possible. Mounting surfaces must be prepped according to manufacturer’s recommendations and the proper mounting torque must be used to mount the accelerometer. Data acquisition systems must be also be configured to eliminate data aliasing and out of band energy contamination[6 and 7].

d. Even if all of the necessary preparatory steps are followed it can still prove difficult to capture accurate acceleration data in the ballistic shock environment. This is because most, if not all, high-*g* accelerometers used in this environment are vulnerable to errors and damage from the broad frequency and high amplitude of the mechanical input. Most high-*g* silicon MEMS accelerometers commercially available have two main vulnerabilities, base-strain sensitivity and resonance susceptibility. High-*g* accelerometers have been produced that can measure upwards of 200,000*g* but are often times undamped and have high resonant frequencies (hundreds of Kilohertz (kHz)). Their high-resonant frequency low-damping design also means there will be a large amplification at the resonance of the seismic mass. Q-Factors of up to 1,000X have been identified[8]. The broad spectrum of ballistic shock almost guarantees some magnitude of frequency content at or near the resonant frequency of the accelerometer. This leaves the accelerometer extremely susceptible to resonance during a ballistic shock event as little power is

required to excite the resonant frequency. Large deflections of vehicle subfloors subjected to underbody blast load can create a strain at the base of the sensor that can cause a DC acceleration output from the accelerometer. Though brief, these DC offsets can accumulate to significant error when integrating acceleration data to obtain velocity information.

e. For these reasons, it is often necessary to perform an "initial validation" of accelerometers to qualify their performance in the ballistic shock test environment before being utilized in a test for record.

3.2 Difference in Shock and Pyroshock.

Readers are encouraged to read carefully from MIL-STD-810G CN1 Methods 516.7 for Shock, 517.2 for Pyroshock, and 522.2 for Ballistic Shock, while utilizing the contents of this TOP to perform any analysis. Thorough explanations of the differences between shock environments are given in the standard. For convenience, the major differences between each category of shock are provided. These were documented in an article in Sound and Vibration Magazine[9] and extracted directly from corresponding sections of MIL-STD 810G CN1.

a. Method 516.7 - Shock.

(1) To evaluate the physical and functional performance of materiel likely to be exposed to mechanically induced shocks in its lifetime.

(2) Generally limited to a frequency range not to exceed 10,000 Hz, and a duration of not more than 1.0 second.

(3) In most cases of mechanical shock, the significant materiel response frequencies will not exceed 4,000 Hz, and the duration of materiel response will not exceed 0.1 second.

b. Method 517.2 - Pyroshock.

(1) Refers to the localized intense mechanical transient response of materiel caused by the detonation of a pyrotechnic device on adjacent structures.

(2) Pyroshocks are generally within a frequency range between 100 and 1,000,000 Hz, and at a duration from 50 microseconds to not more than 20 milliseconds.

(3) Accelerations response amplitudes to pyroshock may range from 300 to 200,000 *g*'s.

(4) Pyroshock usually exhibits no momentum exchange between two bodies (a possible exception is the transfer of strain energy from stress wave propagation from a device through structure to the materiel).

(5) Pyroshock results in essentially no velocity change in the materiel support structure. Frequencies below 100 Hz are never of concern.

c. Method 522.2 - Ballistic Shock.

(1) High-level shock that generally results from the impact of projectiles or ordnance on armored combat vehicles.

(2) Combined low and high frequency (10 - 1,000,000 Hertz (Hz)) and very broadband frequency input.

(3) High acceleration (300 - 1,000,000 *g*'s) with comparatively high structural velocity and displacement.

(4) Usually exhibits momentum exchange between two bodies or between a fluid and a solid.

(5) High residual structure displacement, velocity, and acceleration response (after the event).

3.3 Applicability.

a. The intended purpose is to have available a test methodology that provides a test engineer the framework necessary to analyze new accelerometers and in-house designed mechanical filters.

b. Many technologies exist for the measurement of shock, and this TOP will focus only on accelerometers. Engineering judgement can be used to adapt portions of the TOP to various other shock sensing gauges.

c. This TOP focuses on testing of Piezoresistive (PR) MEMS type shock accelerometers.

(1) PR MEMS accelerometers have historically exhibited the best performance in the ballistic shock environment.

(2) Typically, PR accelerometers have been preferred over PE accelerometers for high frequency shock environments because the PE accelerometers often have a zero shift (change in the nominal DC output) during the shock event[10].

(3) Unless it is clearly demonstrated that a PE accelerometer (mechanically isolated or not) can meet the pyroshock requirements and is designed for oscillatory shock (not one-sided shock pulses), recommend PR accelerometers be used for high intensity pyroshock events[9].

4. TEST PROCEDURES.

4.1 Resonance Characterization.

a. To better understand the operating limitations of the accelerometer, it is helpful to empirically determine its resonant frequency. Exciting and recording the resonant frequency will provide the damping ratio and Q-factor of the gauge, and will also demonstrate characteristics that will enable the engineer to identify artifacts from a resonating accelerometer in actual test data.

b. Producing a mechanical input such as a half-sine pulse, with a duration short enough (<1.5 microseconds (μs)) to excite the resonance can be difficult to do in a precise and controlled manner without specialized lab equipment. In the absence of precise loading fixtures capable of delivering such an input, one of the easiest methods to excite the resonant frequency of an undamped high-*g* MEMS accelerometer is with a #2 mechanical pencil. By simply fracturing a small piece of graphite against the case of the accelerometer, high frequency stress waves are produced at a high enough amplitude to excite gauge resonance. Caution must be used to ensure the graphite is not fractured directly on the sensing element, which may cause gauge damage. It is best to break the lead on the gauge housing away from the sensing element.

c. To measure the resonant frequency of the accelerometer, an oscilloscope capable of recording at least 10x faster than the manufacturer's specified nominal resonant frequency should be used. For this experiment, only the raw output from the gauge is required and signal conditioning/filtering are not used. Using a precision power supply, excitation voltage should be applied at the manufacturer's recommended level (nominally 10 volts (V)). The signal leads should then be fed into the oscilloscope to measure the resulting output from the gauge. Signal leads should be less than 6 ft in total length to ensure filtering from cabling is reduced as much as possible. Configure the scope so the entire free-resonance (<4 milliseconds (ms)) of the gauge can be recorded without clipping.

d. Because of the low-level input, it is unlikely that the mounted resonant frequency of the gauge will be excited. For this, the gauge should not be mounted and torqued to its specified settings. Instead, place the gauge (face up) on a wooden benchtop and hold securely with the tip of your index finger as shown in Figure 1. Extend about 1/16 to 1/8 of an inch of graphite from the pencil and break it on the opposite side of the accelerometer's case. Several attempts will likely be required to achieve the desired effect. Once the signal has been recorded, verify the frequency is in line with the manufacturer's specified values.

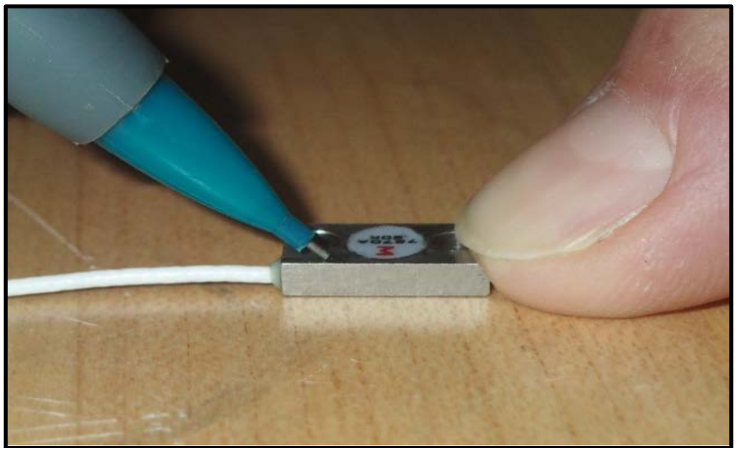

Figure 1. Lead break.

e.   A typical output from the accelerometer excited by lead pencil break is shown in Figure 2. It should be noted that the gauge used in this example was 20,000 *g* in range with a nominal full-scale output of 200 millivolt (mV). Notice that the resulting output is an exponentially damped sinusoid with a peak value more than half the operating range of the sensor (12,000 *g*/120 mV). Also present in the trace are two distinct resonant frequencies resulting from slight variances in the two seismic masses used in the construction of the accelerometer[11]. A Fast Fourier Transform (FFT) of the resulting signal shows the resonant frequencies to be approximately 410 kHz and 430 kHz (see Figure 3). The difference between these two is approximately 20 kHz, which corresponds to the more noticeable beat frequency. This does not indicate a fault with the accelerometer. In this case, each distinct frequency should be calculated and averaged to determine the approximate resonant frequency of the gauge, 420 kHz.

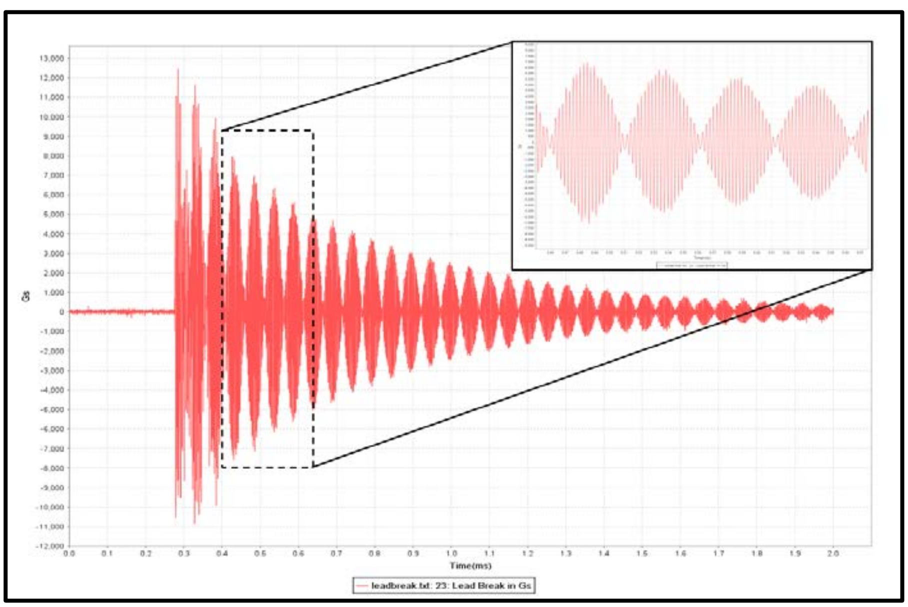

Figure 2. MEMS accelerometer resonance.

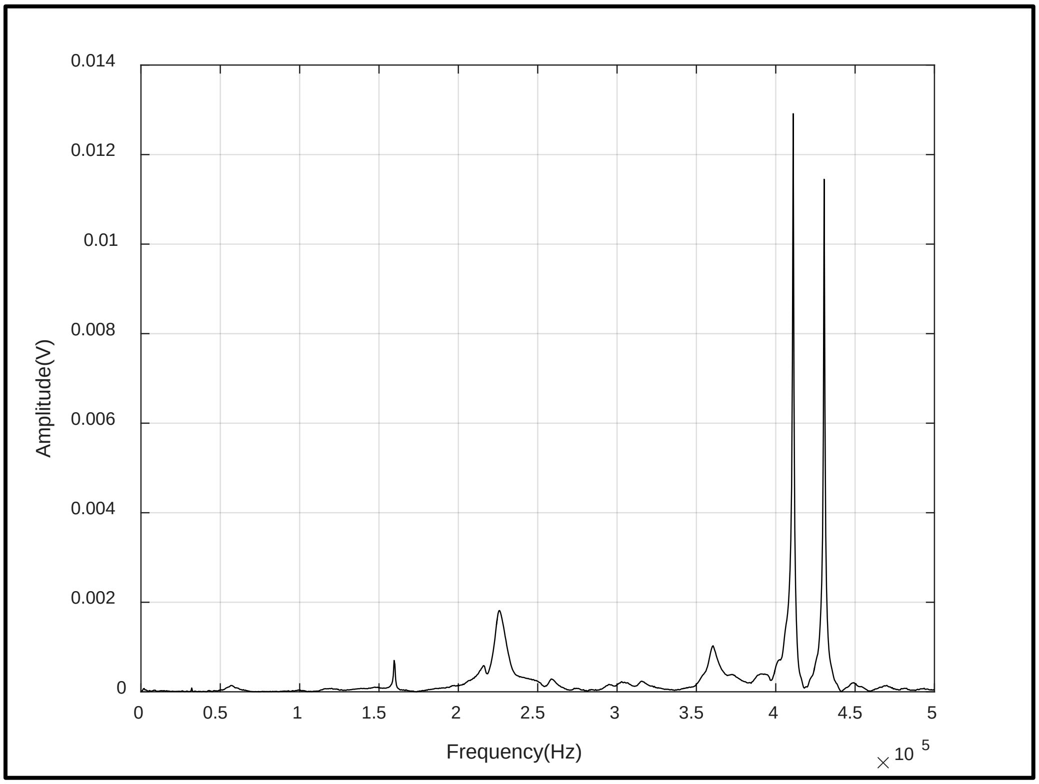

Figure 3. FFT of accelerometer resonance excited by graphite fracture.

f. In the case when a damped accelerometer is being tested or resonance cannot be induced by the method described above, other options exist. One method is to fire a small caliber (~0.177 inch) BB from a BB gun at 100 to 200 meters per second (m/sec) at a steel plate to which the accelerometer is mounted. Though the setup may vary slightly, the steel plate should have a mass and thickness, such that the impact from the BB creates a displacement in the plate of less than 30 microns. Impact of the BB on the plate should produce frequency content high enough to induce resonance in most high-*g* MEMS shock gauges with and without damping.

g. The gauge (Unit Under Test (UUT))) should be attached to the steel plate according to manufacturer's specifications. A LDV should be positioned to measure the plate response just next to the accelerometer (see Figure 4), as a reference to ensure accelerometer resonance has been excited. The same setup described to capture free-resonance should be used in this experiment, with the exception of the mounting the accelerometer to a steel plate. Keep in mind that the amplitude of the response from the BB impact will be much greater than with the mechanical pencil. It is suggested that initial impact locations are far from the mounting location of the accelerometer (> 2 ft) as this test can result in damage to the gauge.

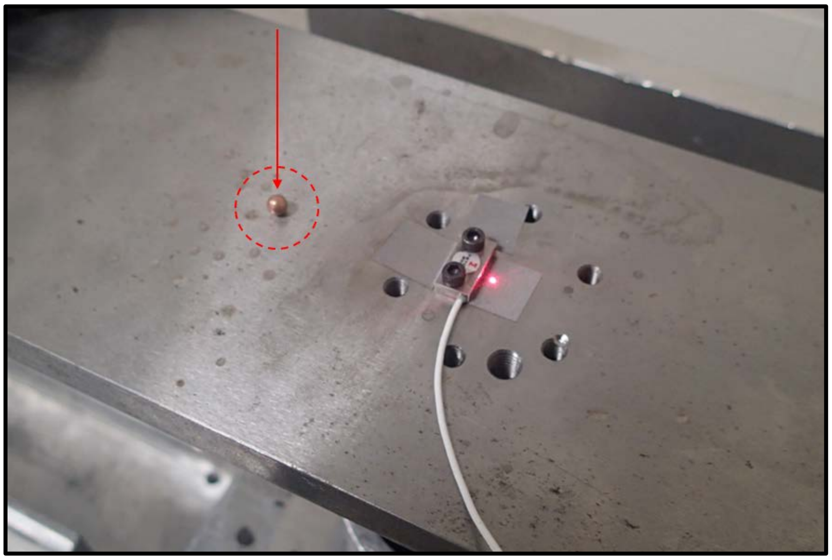

Figure 4. Approximate BB impact location and LDV position.

h. A typical result from the BB impact is shown in Figure 5. The red trace is the output from an undamped MEMS accelerometer while the black trace is the acceleration as recorded by the LDV (differentiated velocity). As the figure shows, there is significant short duration amplitude created by the low energy impact of the BB which excites the resonant frequency of the accelerometer. After impact, the accelerometer continues to resonate at levels well above the true value as reported by the LDV. A FFT of the accelerometer output is shown in Figure 6.

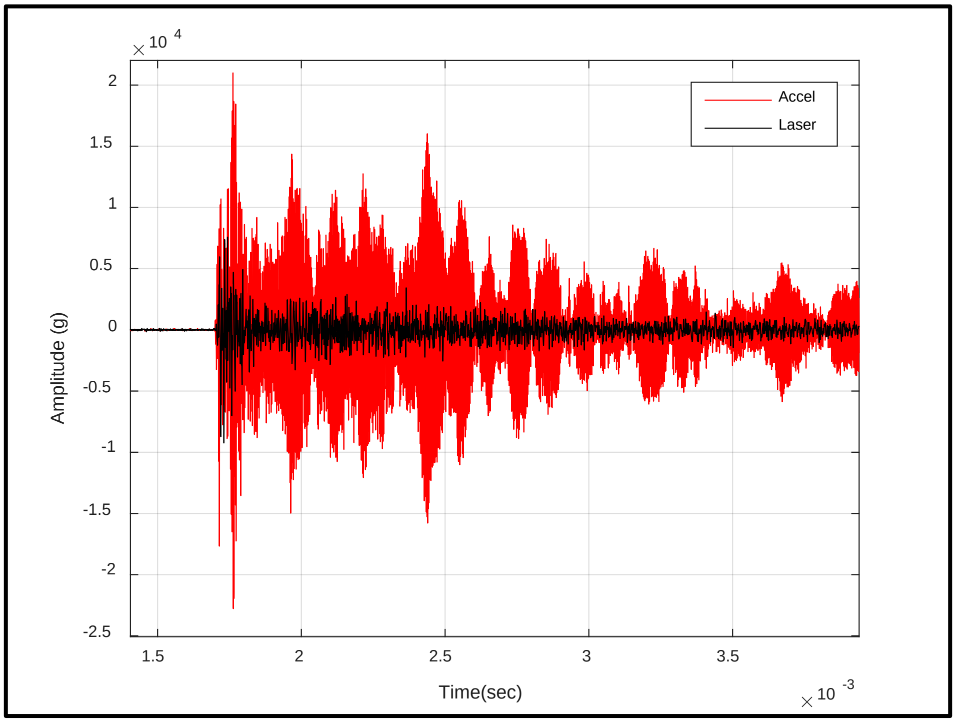

Figure 5. Accelerometer resonance from BB impact.

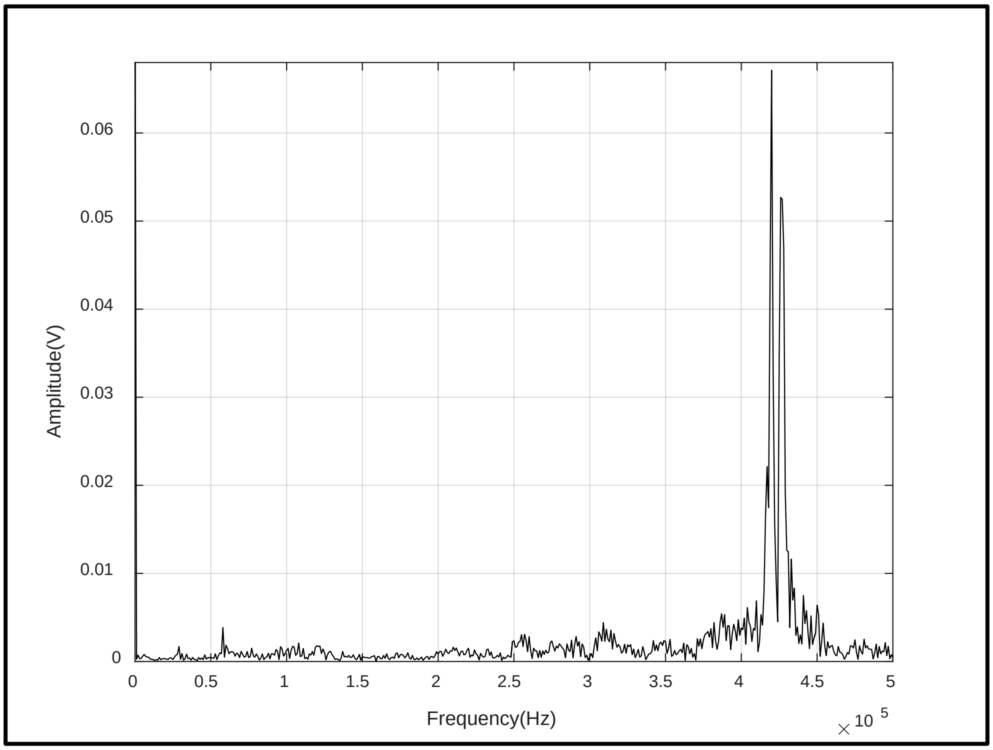

Figure 6. FFT of accelerometer resonance from BB impact.

i. Output from the accelerometer at resonance should be used to determine the approximate Q-factor (amplification at resonance) and damping ratio. There are several methods that can be used to approximate these values; the half-power is used in this example as the log-decrement is not easily computed because of the interfering resonant frequencies.

j. Using the computed FFT, the frequency of the lowest fundamental should be noted as, f_n, the natural frequency. A line corresponding to the max value of the amplitude at this frequency divided by the square root of two (-3 decibels (dB) in log scale) from the peak amplitude of the fundamental should be drawn as shown in Figure 7. The two points at which the Frequency Response Function (FRF) passes this line should be recorded as f_1 and f_2. Amplification at resonance or Q-factor is defined in Equation 1 along with the damping ratio in Equation 2. This technique can be used to determine the approximate Q-factor and damping ratio of the example accelerometer. The resulting Q-factor indicates that at resonance the true mechanical input is magnified by 633X.

$$\boldsymbol{Q-Factor}: Q = \frac{f_n}{f_2 - f_1} = \frac{411{,}000}{411{,}308 - 410{,}659} = 633 \qquad \textit{(Equation 1)}$$

$$\boldsymbol{Damping\ Ratio}: \zeta = \frac{1}{2Q} = \frac{1}{2*633} = 0.00079 = 0.079\% \qquad \textit{(Equation 2)}$$

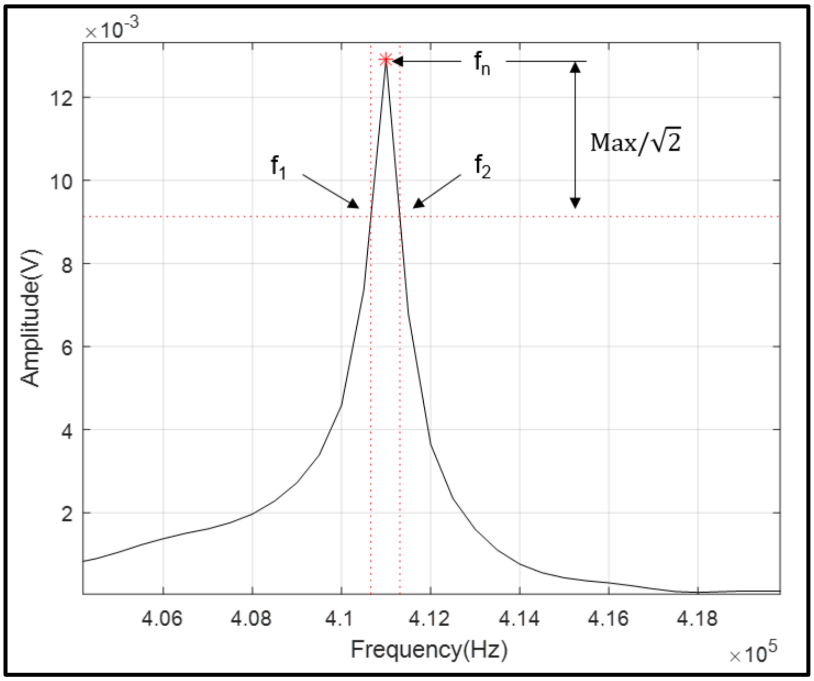

Figure 7. Half-power method for Q-factor and damping ratio.

k. A second method to calculate the Q-factor and damping ratio is to fit an exponential line to the decay envelope of UUT output at resonance, as represented by the black line in Figure 8a. Using the averaged resonance frequency, a damped sinusoid can be constructed to approximate the resonant response, less the destructive beat frequency as represented by the blue trace in Figure 8b.

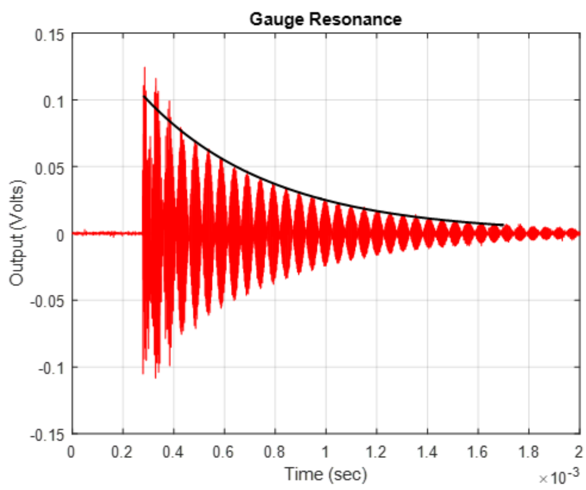

Figure 8a

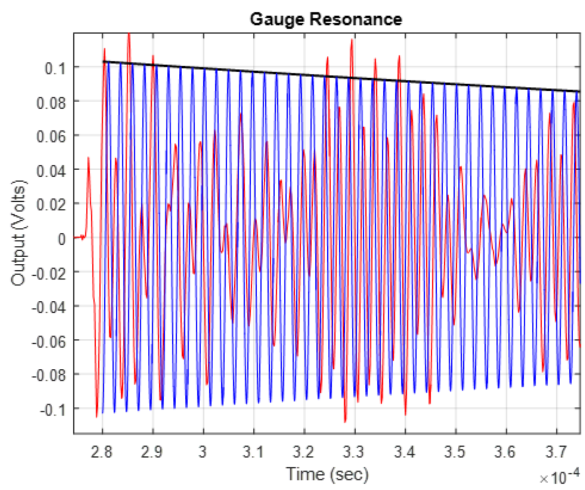

Figure 8b

Figure 8. Resonance decay envelope (8a) and approximated resonance response (8b).

l. The log-decrement can be used on the approximated resonance to determine the desired values. First, the amplitude of any two successive peaks of the signal must be measured, such as shown in Figure 9. Damping ratio can be calculated by Equation 4, using the log decrement calculated from the measured values according to Equation 3. Finally, the Q-factor is calculated according to Equation 5. The resulting values are similar to those calculated in Equations 1 and 2. Ultimately either method may be used as long as accelerometer resonance is excited and analyzed to determine the desired factors.

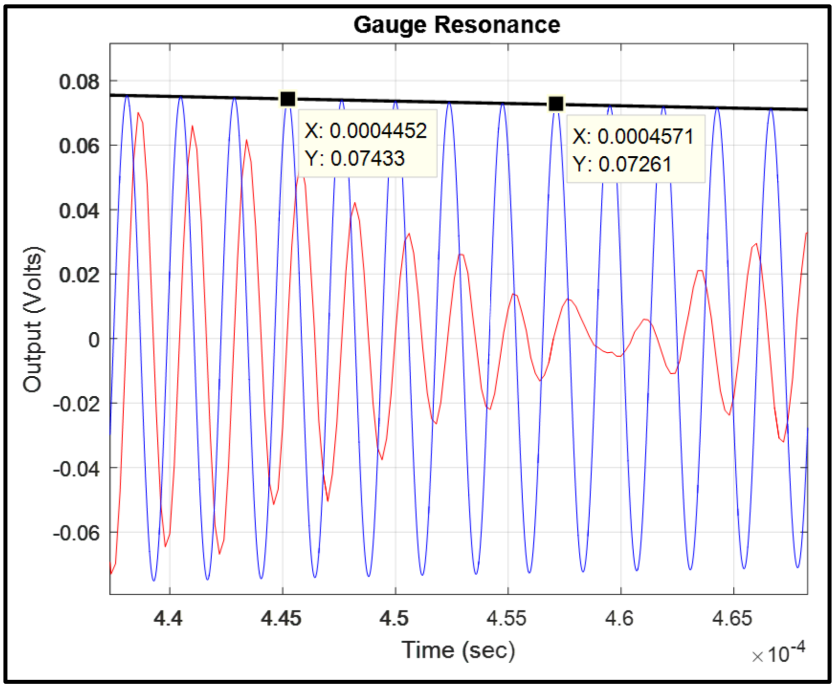

Figure 9. Log decrement measurements.

$$\boldsymbol{Log\ Decrement}:\ \delta = \frac{1}{n}\ln\left(\frac{x_i}{x_{i+n}}\right) = \frac{1}{5}\ln\left(\frac{0.07433}{0.07261}\right) = 0.00468 \qquad (Equation\ 3)$$

$$\boldsymbol{Damping\ Ratio}:\ \zeta = \frac{1}{\sqrt{1+\left(\frac{2\pi}{\delta}\right)^2}} = \frac{1}{\sqrt{1+\left(\frac{2\pi}{0.00468}\right)^2}} = 0.000745 = 0.075\% \qquad (Equation\ 4)$$

$$\boldsymbol{Q - Factor}:\ Q = \frac{1}{2\zeta} = \frac{1}{2(0.000745)} = 671 \qquad (Equation\ 5)$$

4.2 <u>Base Strain Quantification</u>.

a. One of the suspected sources of measurement error resulting from the use of high-*g* MEMS accelerometers is base strain sensitivity, or the erroneous signal output when strained, primarily from bending. Ballistic shock is an oscillatory shock and in many locations of interest, such as vehicle subfloors loaded from an underbody blast, contains many surface deflections. These cyclic deflections can cause numerous DC shifts in the output from the accelerometer, that while not noticeable in the acceleration-time history, accumulate large errors during the integration process and are present in the velocity time history. For these reasons it is important to minimize, or at least have a quantified understanding of the accelerometer's base strain sensitivity, prior to tests for record.

b. As with many of the subtests in this TOP, there may be different methods to achieve the same result. This test setup was found to be effective and is to be used as a guide for the technique. To conduct this test, a method of applying a controlled quasi-static load, such as a load bench as shown in Figure 10, is required. A mild steel beam measuring 4 inches x 0.5 inch x 36 inches was drilled and tapped so that the accelerometer could be attached at the center of the beam. Directly next to the accelerometer a foil type strain gauge was applied with the primary sensing axis parallel to the length of the beam, as shown in Figure 11.

Figure 10. Load bench used for base strain test.

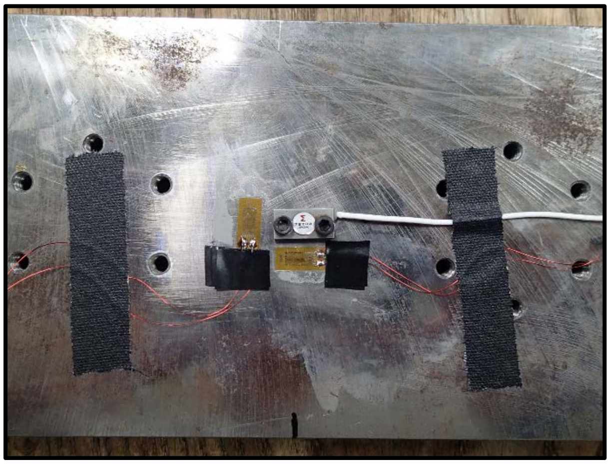

Figure 11. Strain gauge next to accelerometer.

c. The beam was then placed on top of steel uprights spaced approximately 11 inches apart and positioned in the load bench as shown in Figure 12. The beam was positioned such that the accelerometer bisected the span of the uprights and faced down so a force could be applied to the opposite side of the beam directly on top of the gage. Using the load bench, a force was applied to the center of the beam, on top of the accelerometer, at a rate of 135 pounds-force per second. Output from the strain gauge was monitored until a strain of approximately 340 microstrain was achieved. During this process the output from the accelerometer was recorded. A graph of the resulting strain at the base of the accelerometer (red-trace) and the corresponding accelerometer output (blue-trace) is shown in Figure 13.

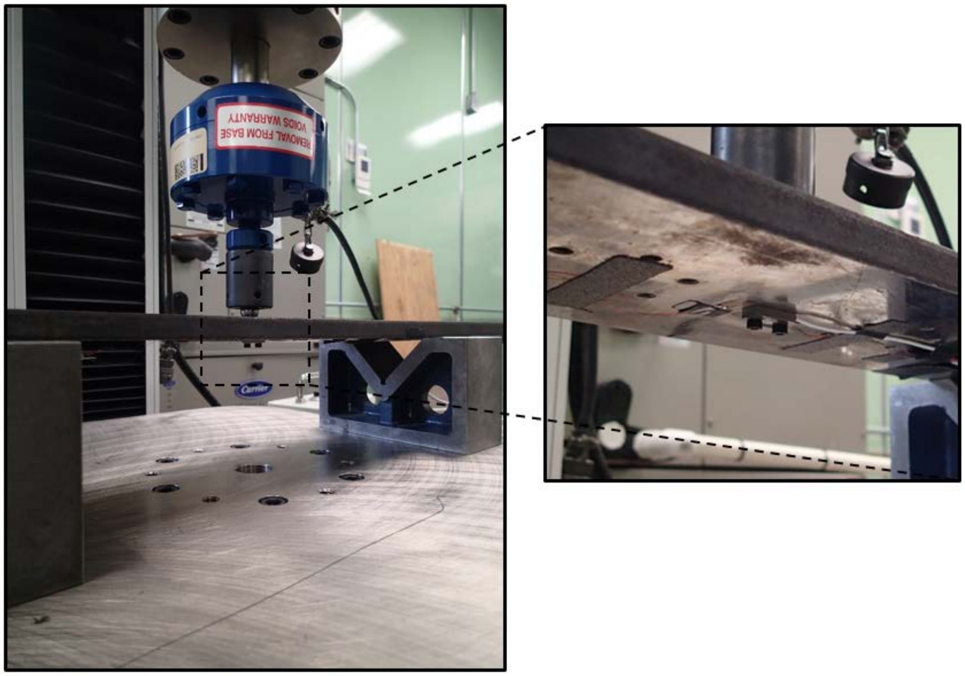

Figure 12. Beam in load bench.

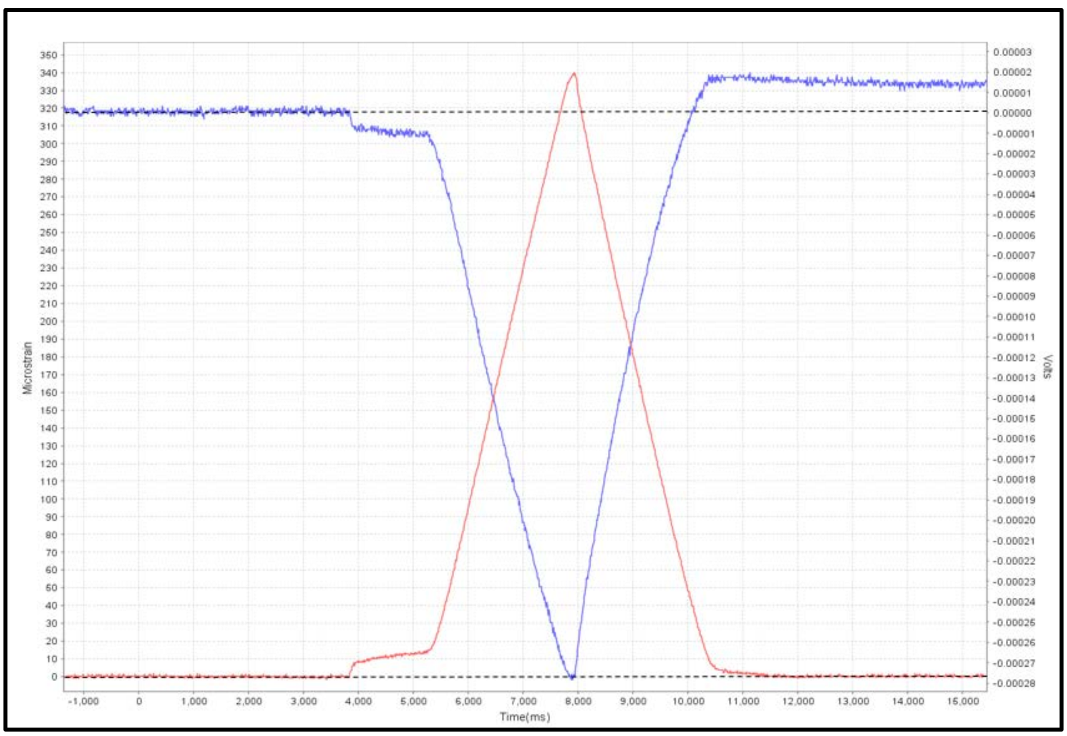

Figure 13. Accelerometer and strain gauge output from base strain test.

d. A base strain sensitivity of 0.812 microvolt per microstrain (μV/με), was determined by dividing the peak voltage output from the accelerometer, 0.276 mV (gain removed) by the peak strain value, 340 με. This value is in-line with the manufacturer's specification of less than 0.5 mV output at 250 με or 2 μV/με.

e. There is no specific requirement for base strain sensitivity for ballistic shock accelerometers, however a high base strain sensitivity may result in decreased amplitude and frequency linearity in subsequent testing. Strain levels can be thousands of microstrain in the ballistic shock environment; an ideal base strain sensitivity, though unrealistic, is zero. This metric can be used to assist the engineer in transducer selection prior to testing when it is known it will be in a high-strain environment.

4.3 Amplitude Linearity.

a. Testing can now be conducted to determine the linearity of the gauge across its operating range. Method 516 for Shock, and Method 517 for Pyroshock, have linearity requirements for accelerometers. Method 516 states, "*In order to understand the non-linear amplification and frequency characteristics, it is recommended that shock linearity evaluations be conducted at intervals of 20 to 30 percent of the rated amplitude range of the accelerometer to identify the actual amplitude and frequency linearity characteristics and useable amplitude and frequency range*." Method 522 (MIL-STD-810G CN1) does not specify linearity requirements, but it is recommended that linearity evaluations be conducted anyway. The intent of this TOP is not to suggest that this routine should be performed on every accelerometer before every test. However, it is recommended that this test is performed in the validation of new accelerometer models, manufacturing changes to existing models, and any other changes made to SOP before use in testing.

b. A shock test machine similar to what is referred to as the "Smack Bar", shown below in Figure 14, will be required for this portion. The Smack Bar (designed by Texas Christian University students) consists primarily of a compressed air gun that fires a steel projectile at a flat steel bar fixed on either end to spring steel and base supports. A three inch long, rounded steel slug is launched from the compressed air gun and impacts the underside of the 36 inches x 4 inches x 0.5 of an inch thick steel bar on which the test accelerometer is mounted. Overhead and isolated from the vibrations of the smack bar, the LDV is positioned to provide a reference or "truth" measurement just next to the item under test. Note, this is not the only test apparatus that may be used. Any shock test apparatus capable of producing the required shock pulses (amplitude and duration) while allowing for reference measurement via the LDV is acceptable.

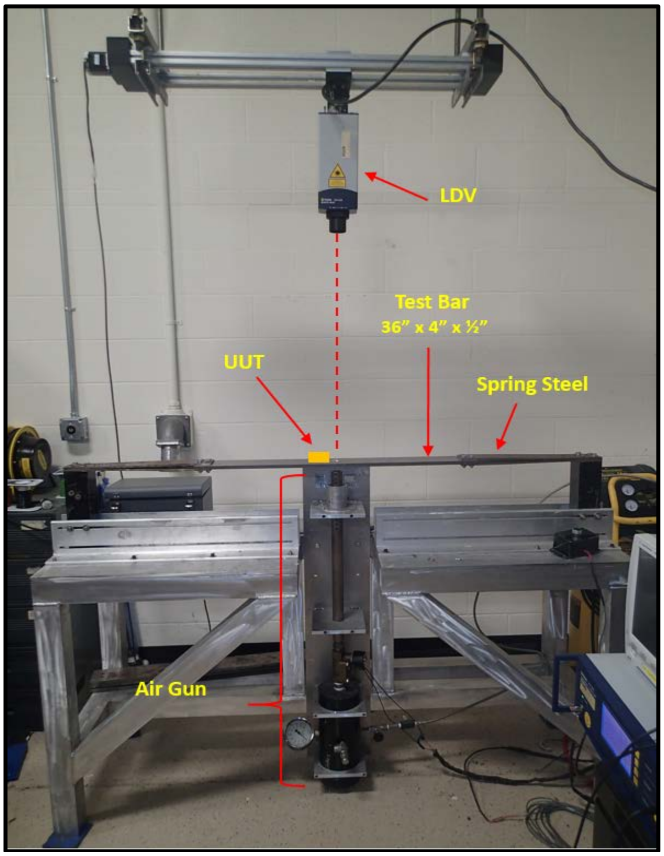

Figure 14. Smack Bbar.

c. A series of test shots using only the LDV should be conducted to determine the appropriate settings such as air gun pressure, projectile and programmer type that will yield the desired accelerations and pulse widths. Borrowing from Methods 516 and 517, the default pulse duration for f_{max} = 10,000 Hz should be approximately 50 micro seconds[7], as shown in Equation 6.

$$T_D = \frac{1}{2f_{max}} = \frac{1}{2(10{,}000Hz)} = 50\ \mu s \qquad \textit{(Equation 6)}$$

(1) A programmer is defined as any type of material placed between the projectile and the impact location on the steel beam to which the UUT is attached. Its purpose is reduce the mechanical response of the steel beam from the impact of the projectile to a desired level.

(2) In general, direct mount accelerometers (not mechanically isolated) should not be used to measure ballistic shock content above 10 kHz. Although their high resonant frequency warrants use up to at least 80 kHz (1/5 resonant frequency) it is reasonable to assume that if there is content between 10-80 kHz, there is likely enough content to excite resonance. If it is desired to measure less than 10 kHz in an environment where >10 kHz input is expected, a mechanical

filter must be used. If measurement of the full Ballistic Shock spectrum is required, another device, such as a velocity coil, should be used.

d. At a minimum, test levels need to be identified that test four points along the rated amplitude range of the UUT, up to ± 10% of the full scale range. An example output from the "LDV only" test shots, for a 20,000 *g* accelerometer, is shown in Figure 15. For this example, the LDV was configured to measure up to 4 m/s at 2.5 MHz and the output was recorded at 5 MSPS digitally filtered with a phase-less low-pass filter at 100 kHz and differentiated to produce acceleration.

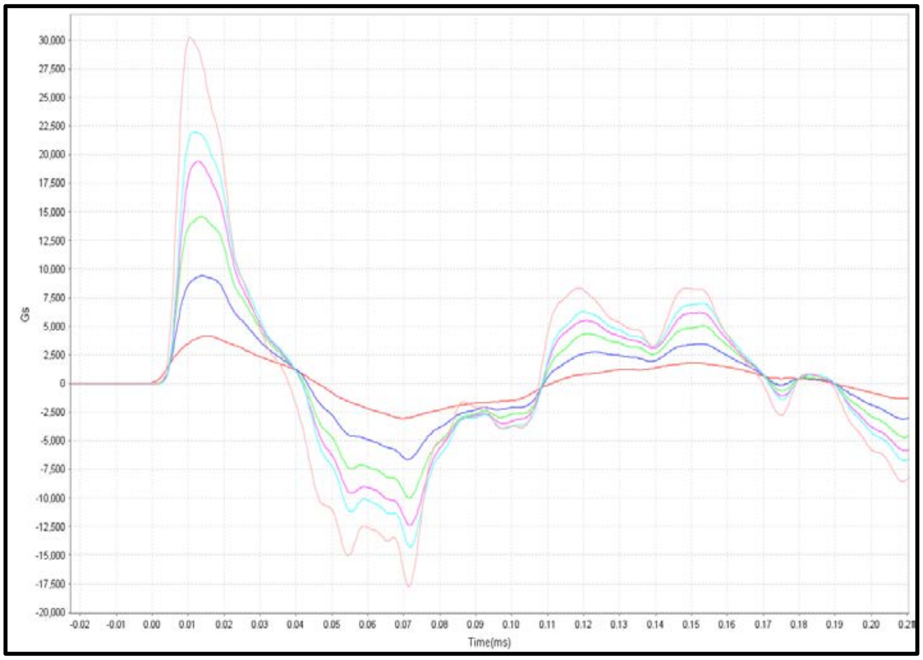

Figure 15. LDV only test shots.

e. Once appropriate test levels have been determined, testing with the accelerometer can begin. Attach the gauge to the smack bar using the mounting torque as specified by the manufacturer. The UUT should be installed on the center of the test bar directly over the impact location of the projectile. Ideally the laser should be aimed as close as possible to the accelerometer while maintaining perpendicularity of the laser to the test beam to eliminate error, as shown in Figure 16. If this is not possible, position the UUT and the laser equidistance from the impact location of the projectile. Using the settings determined in pre-test preparation, proceed with testing.

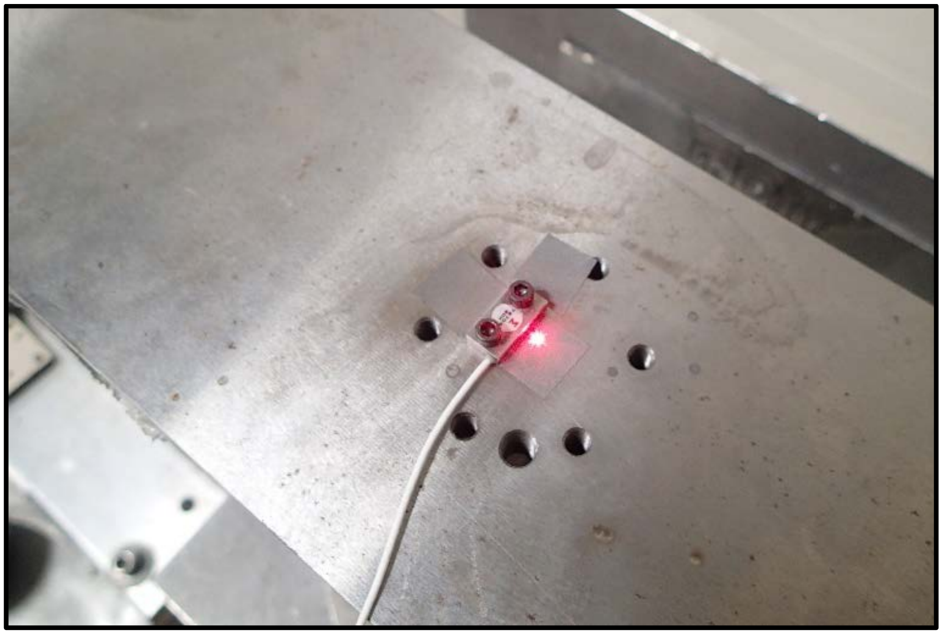

Figure 16. Laser positioning for smack bar testing.

f. After each impact, the Zero Measurand Output (ZMO) from the accelerometer should be recorded. The ZMO is the voltage present on the accelerometer's output at 0 *g*'s. The ZMO can be measured by applying the specified excitation voltage to the UUT and measuring the output on the DVM. In practice, the ZMO will never be zero but should always be within ± 100 mV of zero. Slight variations in the ZMO from test to test are expected and are indicative of zero-shifts due to high shock. It is recommended that ZMO should vary less than ± 10 percent from the calibrated value throughout testing conducted within the specified range of the UUT. An example of the resulting ZMO plot can be found in Figure 17.

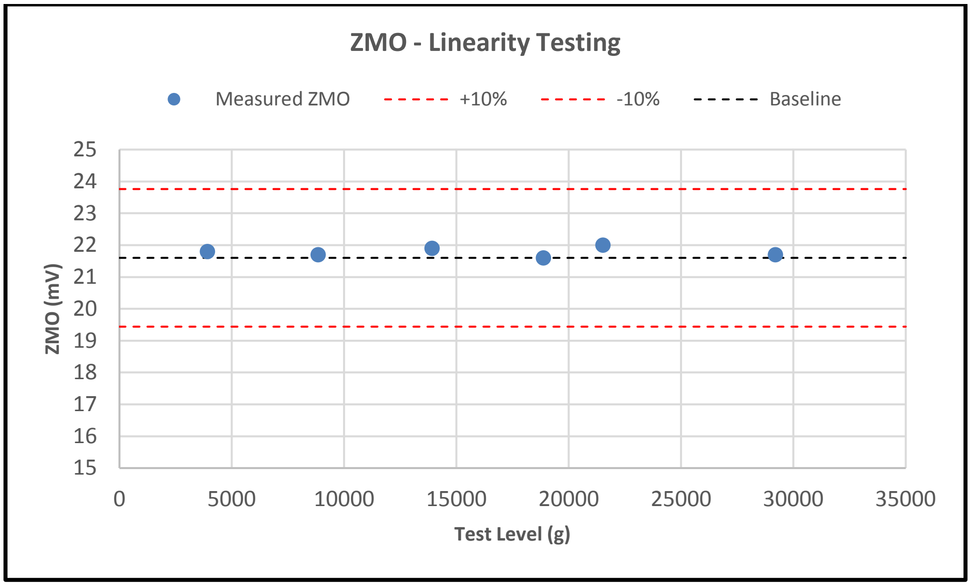

Figure 17. ZMO change from testing.

g. A typical response from both the LDV and UUT are shown in Figure 18. The solid line represents the output from the UUT and the dashed line is the output form the LDV. Each was sampled at 5 MHz and digitally filtered at 100 kHz. This process should be repeated until all test levels are met.

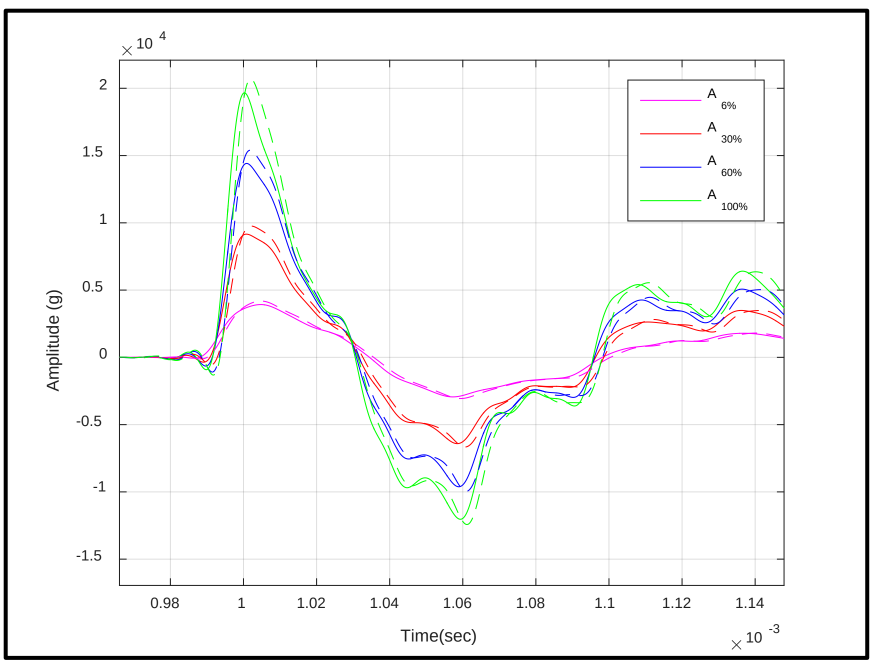

Figure 18. LDV and UUT response to amplitude linearity check.

h. Upon completion of testing, results should show amplitude agreement within ± 10 percent of the LDV. An example amplitude linearity plot is shown in Figure 19. The black x's represent the acceleration measured from the LDV (x-axis) compared to the acceleration measured by the UUT (y-axis). A linear least squares fit line was added to the data (black dotted line) along with ± 10 percent corridors from the LDV.

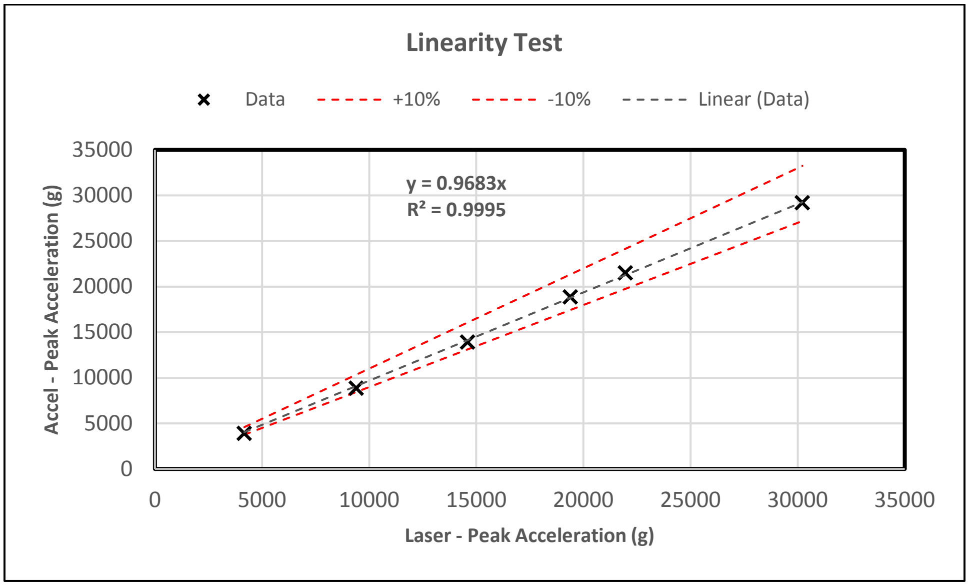

Figure 19. Amplitude linearity example.

4.4 Frequency Response.

a. Frequency response testing utilizing a PE shaker table is not required. Although this testing can be performed to determine amplitude and phase agreement in the lower frequency, it is considered optional as it does not represent an operationally similar input. The input from the shaker is too low (10 *g* for most testing) and covers less than 0.1% of full scale for most ballistic shock accelerometers.

b. Test results from the amplitude linearity subtest can be analyzed to determine appropriate frequency response over the bandwidth of interest. It is important to determine the frequency response up to the full scale range of the accelerometer, as it can vary from the response at lower level inputs. To accomplish this, a minimum of four impacts from the amplitude linearity study should be surveyed. As an example, the traces shown in Figure 18, representing approximately 6, 30, 60 and 100 percent of the full scale range of the accelerometer are used.

c. First, a Fourier Transform should be produced and used to verify that the majority of the frequency content falls within the bandwidth of interest, in this case 100-10,000 Hz as shown in Figure 20. Prior to spectral analysis, both accelerometer and LDV results should be digitally

filtered to 100 kHz. The derivative of the filtered LDV results should be taken to produce acceleration and should be used for the remainder of spectral analysis. The dotted lines in the figure represent the Fourier Transform of the acceleration calculated from the LDV data.

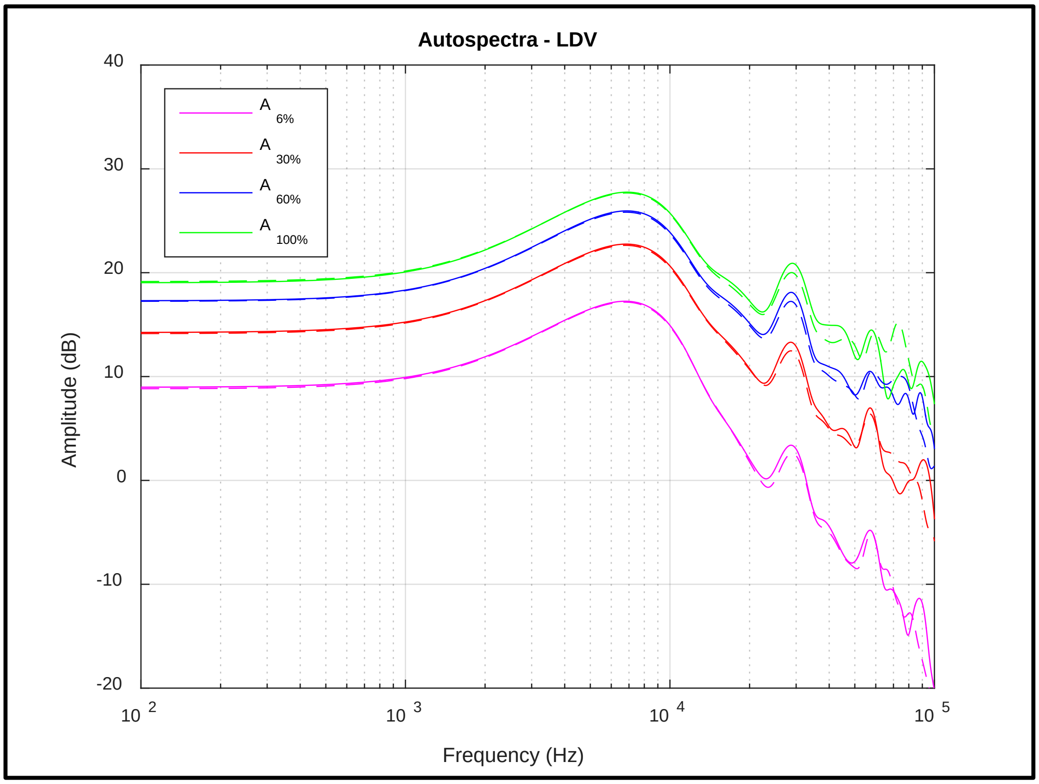

Figure 20. Fourier Transform of linearity data.

d. Results from the Fourier Transform data are then used to construct a FRF between the UUT and the LDV. The FRF is calculated using Equations 7 - 10.

$$H(j\omega) = \frac{H_1 + H_2}{2} \qquad \text{(Equation 7)}$$

$$H_1(j\omega) = \frac{G_{xy}}{G_{xx}} \qquad \textit{(Equation 8)}$$

$$H_2(j\omega) = \frac{G_{yy}}{G_{yx}} \qquad \textit{(Equation 9)}$$

$$\gamma_{xy}(j\omega)^2 = \frac{H_1}{H_2} \qquad \textit{(Equation 10)}$$

where:

G_{xy} is the Cross-Spectrum between the LDV(x) and the UUT(y)
G_{yx} is the Cross-Spectrum between the UUT(y) and the LDV(x)
G_{yy} is the Auto-Spectrum of the UUT(y)
G_{xx} is the Auto-Spectrum of the LDV(x)

e. The resulting FRF of the data in Figure 20 is shown in Figure 21. An FRF is included for each of the four test amplitudes as indicated by the legend. Also included is the averaged FRF of the four test conditions, represented by the black trace. There is no flatness requirement for the frequency response of Ballistic Shock transducers. Pyroshock, however, specifies a flat response within ± 5 percent across the frequency range of interest[11]. The red dotted lines represent ± 10 percent.

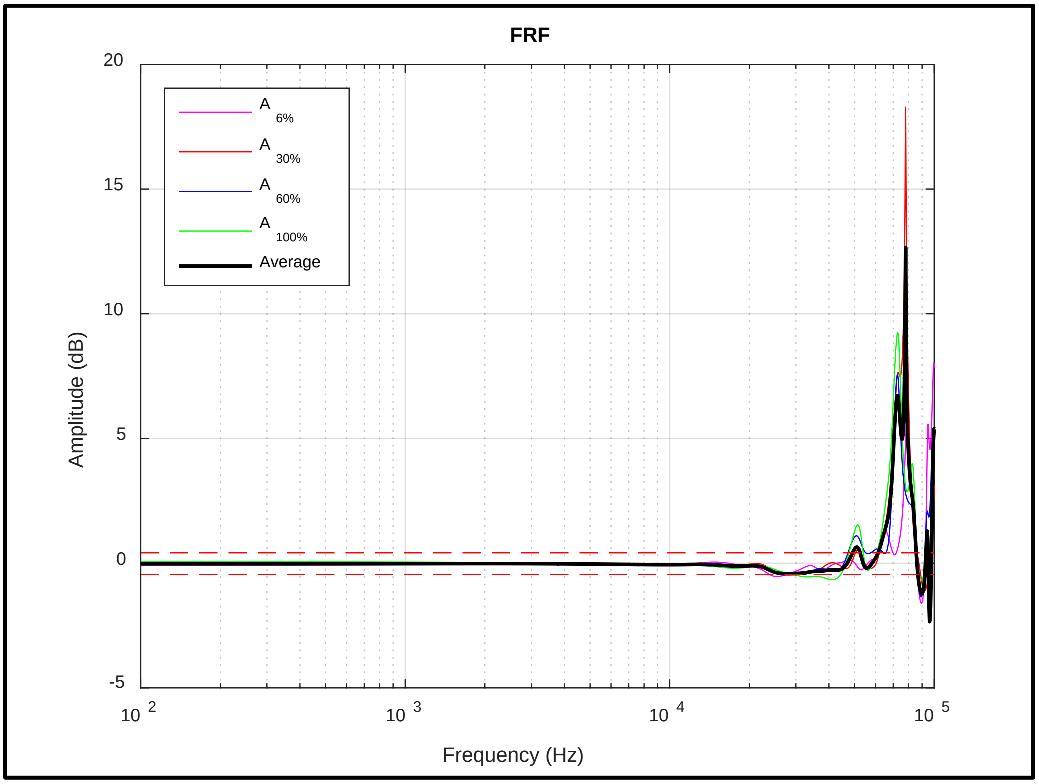

Figure 21. FRF of linearity data.

f. The Coherence plot, corresponding to the data in Figure 18, is shown in Figure 22. A Coherence value of one shows strong agreement between the two signals. Nominally, the

coherence of the averaged four test cases should be between 0.9 and 1.0 through the operating bandwidth of the UUT[11].

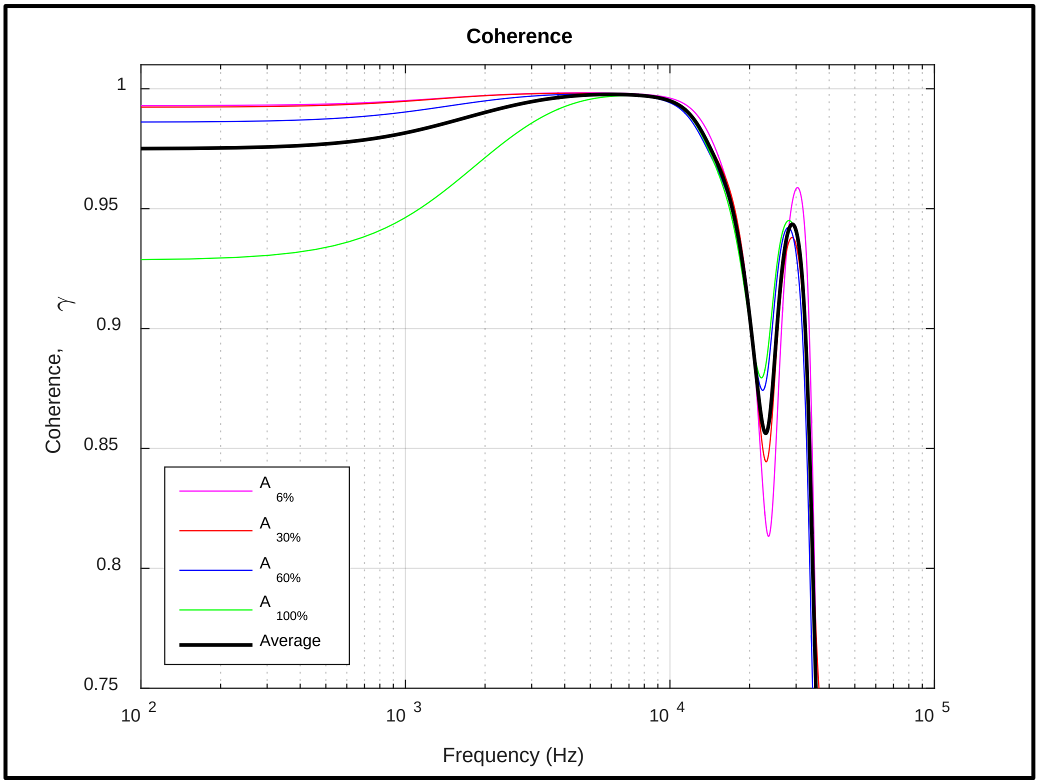

Figure 22. Coherence of linearity data.

4.5 Transverse Sensitivity.

a. Transverse sensitivity testing should be conducted to determine the accelerometer's sensitivity to input perpendicular to its sensing axis. The shock machine should be modified to allow for input to the UUT to be primarily in one axis, eliminating input (as much as possible) to the sensitive axis. Because of the plate kinematics, testing the transverse axis with the UUT mounted on a steel plate may allow too much motion in the sensitive axis to provide meaningful results. As a result, setup from the Amplitude Linearity section can be repeated with the UUT mounted perpendicular to the input from the shock machine, but the setup described in the remainder of the section is preferred.

b. A steel rod, with outer diameter matching the inside diameter of the gas gun was modified so a transverse mounting block could be attached, as shown in Figure 23. The transverse mounting block, shown in the enhanced view of Figure 23, allows the accelerometer to be mounted perpendicular to the input from the air gun. Reflective film was placed on the top of the mounting block and the LDV was aimed just above the mounting location of the UUT to measure the vertical input to the gauge.

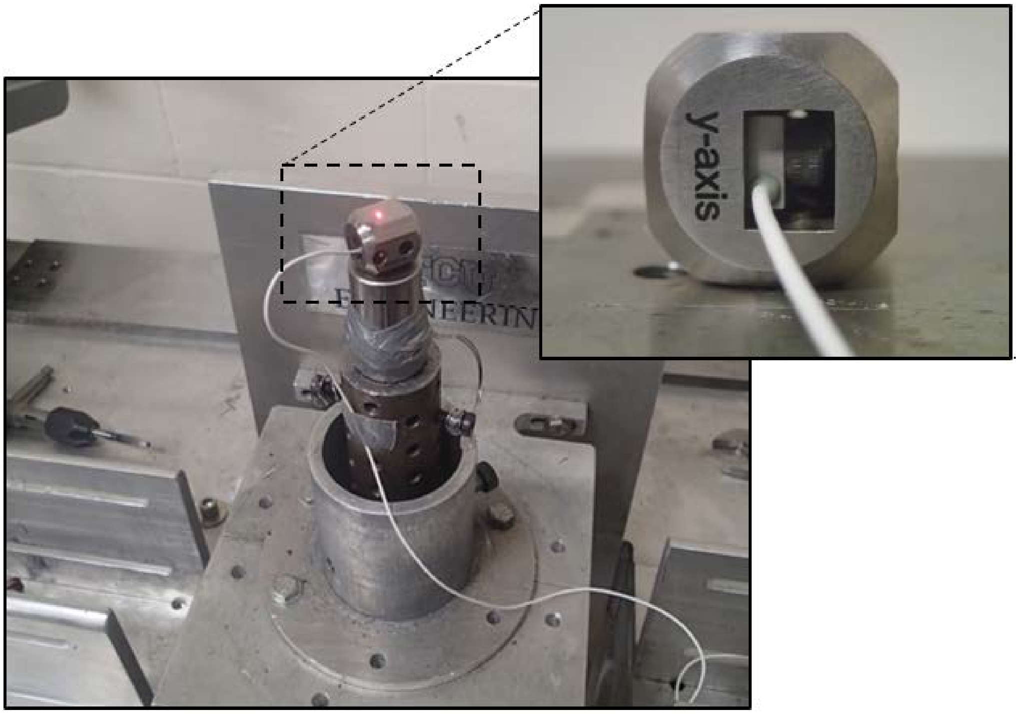

Figure 23. Transverse sensitivity test setup.

c. Prior to installing the accelerometer, a series of shots should be performed with the LDV only, to ensure setup parameters that will allow for a series of inputs that span the operating range of the gauge. Testing with the UUT can proceed when it is determined that the response (as measured from the LDV) matches the operating limits of the UUT, such as full-scale amplitude and frequency content. For example, if the UUT has a full-scale range of 20,000 *g* and can measure a frequency response of 80,000 Hz, the LDV only test should confirm that the test apparatus can generate that response. A minimum of four inputs should be used, the highest of which should be within 10% of the full-scale rated range of the gauge. The pulse width of the input should be approximately 50 µs, matching the 10 kHz frequency response or the operating range of the gauge. Figure 24 shows the acceleration input pulses used for this experiment as measured by the LDV. Proceed with testing until the desired number of tests have been completed.

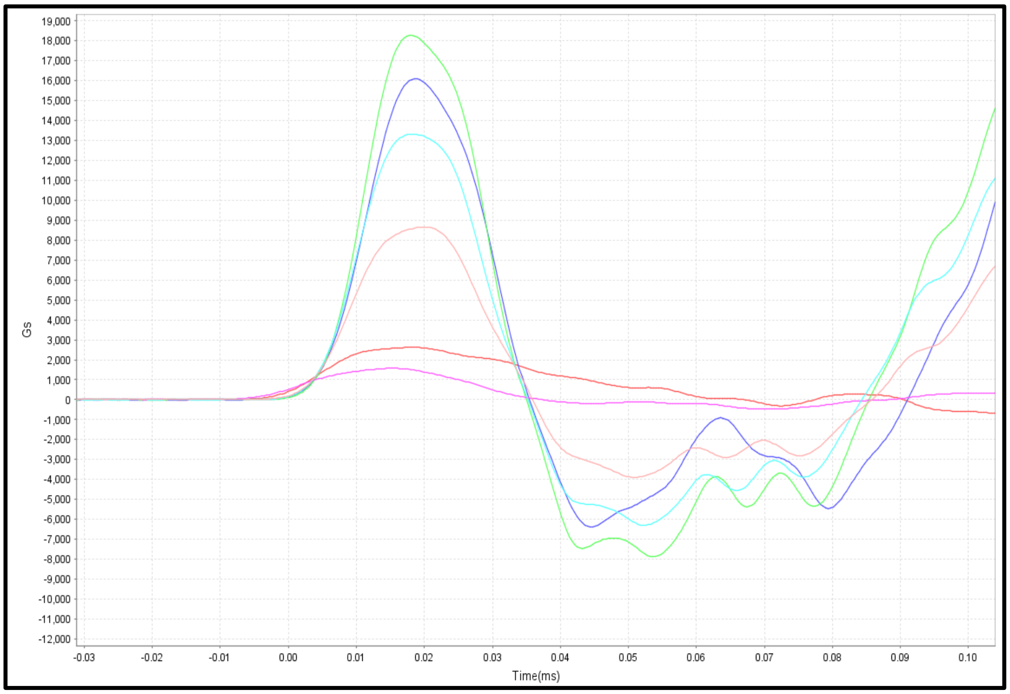

Figure 24. Transverse sensitivity input acceleration.

d. A typical output from the accelerometer resulting from the transverse sensitivity test is shown in Figure 25. The red-trace is the differentiated velocity data from the LDV and the blue-trace is the acceleration data from the UUT. Ideally, the output from the UUT from an impact in the transverse axis should be zero, but in practice, there will always be some transmission to the sensitive axis. Many high-*g* MEMS accelerometers come from the manufacturer with a transverse sensitivity rating; the gauge tested in this example was specified to have a transverse sensitivity of less than 5%.

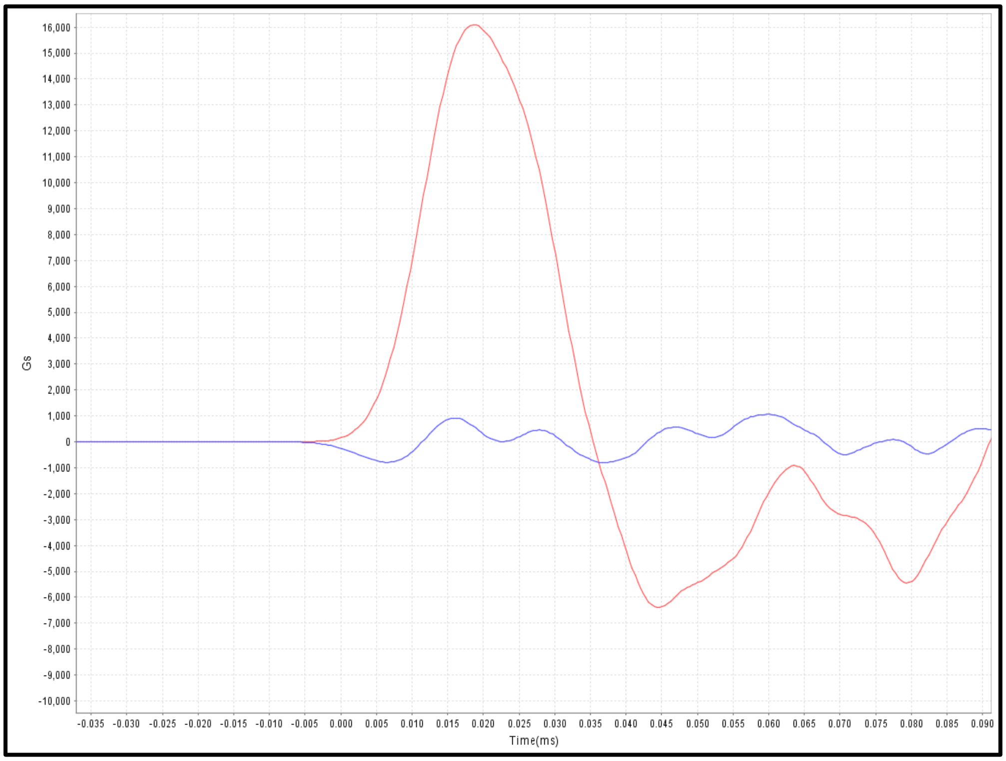

Figure 25. Example input/output comparison, transverse sensitivity testing.

e. Output from the UUT resulting from the impacts shown in Figure 24 are shown in Figure 26. The dotted green lines in the figure represent ± 5% of the peak acceleration as measured from the LDV along the impacted axis. The dotted red lines represent ± 10% of the peak acceleration as measured from the LDV along the impacted axis. As shown, the transverse sensitivity exceeds 5% (manufacturer's specification) at input accelerations above approximately 15,000 *g*. Although this exceeds the manufacturer's specification, transverse sensitivities less than 10% are considered acceptable in certain circumstances.

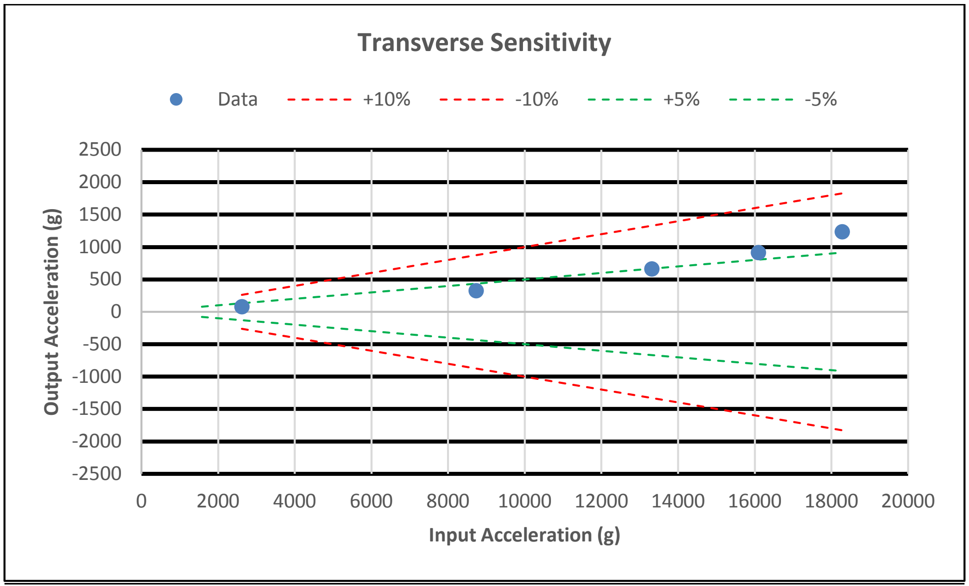

Figure 26. Typical transverse sensitivity curve.

4.6 <u>Full-Spectrum Smack Bar Testing</u>.

a. Up to this point in the TOP, only an abbreviated portion of the full spectrum of Ballistic Shock has been used to assess accelerometers. However, Method 522.2 of MIL-STD-810G CN1 states that “transducers used in ballistic shock applications must be evaluated in the ballistic shock environment (roughly 1 MHz, roughly 1 million *g*)”. This statement was made with the assumption that some sort of mechanical filter would be used in mounting the accelerometer, it isn’t logical to expect a direct mounted accelerometer to survive this environment. Mechanical filters are a necessity to measure full-scale ballistic shock data with accelerometers. Figure 27 shows a conceptual representation of the FRF of a mechanical filter with the FRF of an accelerometer. As depicted, the main purpose of the mechanical filter is to protect the accelerometer from mechanical inputs that could excite its resonant frequency.

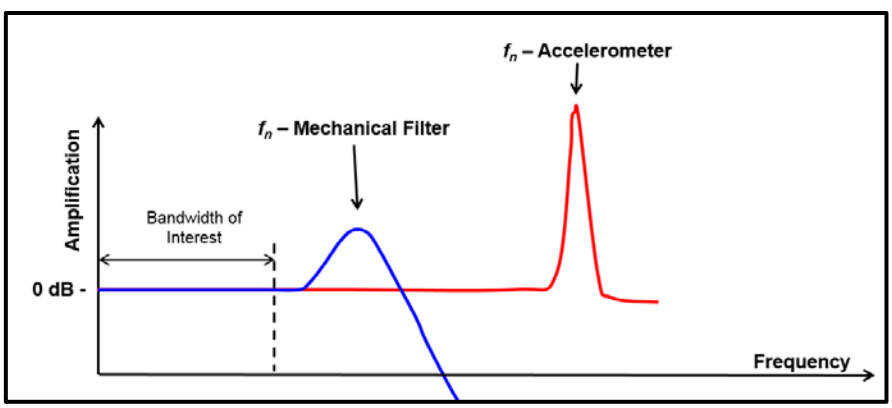

Figure 27. Ideal FRF of mechanical filter.

b. To measure the entire range of ballistic shock, different varieties of mechanical filters are used, each designed to measure a specific frequency range of the total spectrum. When pieced together, it is the response from multiple sensors that is used to measure the entirety of the spectrum. As Method 522.2 states:

> *"In general, ballistic shock measurements require the use of at least two different measurement technologies to cross check each other for validity. In addition, the frequency spectrum of ballistic shock content is generally so wide (10 Hz to more than 100,000 Hz) that no single transducer can make valid measurements over the entire spectrum."*
>
> *"Figure 522.2-2* (Figure 28) *illustrates the limited "useful frequency range" of three different transducers. Note that the ATC Velocity Coil has a noticeable resonance at 70 Hz, but it agrees with the BOBKAT sensor from 300 Hz to 1,000 Hz, and provides useful data out to 1 MHz. The BOBKAT sensor indicates erroneous values below 30 Hz, and above 2 KHz, but agrees with the LOFFI from 30 Hz to 150 Hz and agrees with the ATC Velocity Coil from 400 Hz to 1 KHz. The LOFFI sensor provides useful data from 5 Hz to 150 Hz. The resonant frequency, damping ratio, and useful frequency range of each transducer should be taken into consideration and must be documented, so that transducer anomalies can be identified, if present in the measurement data."*

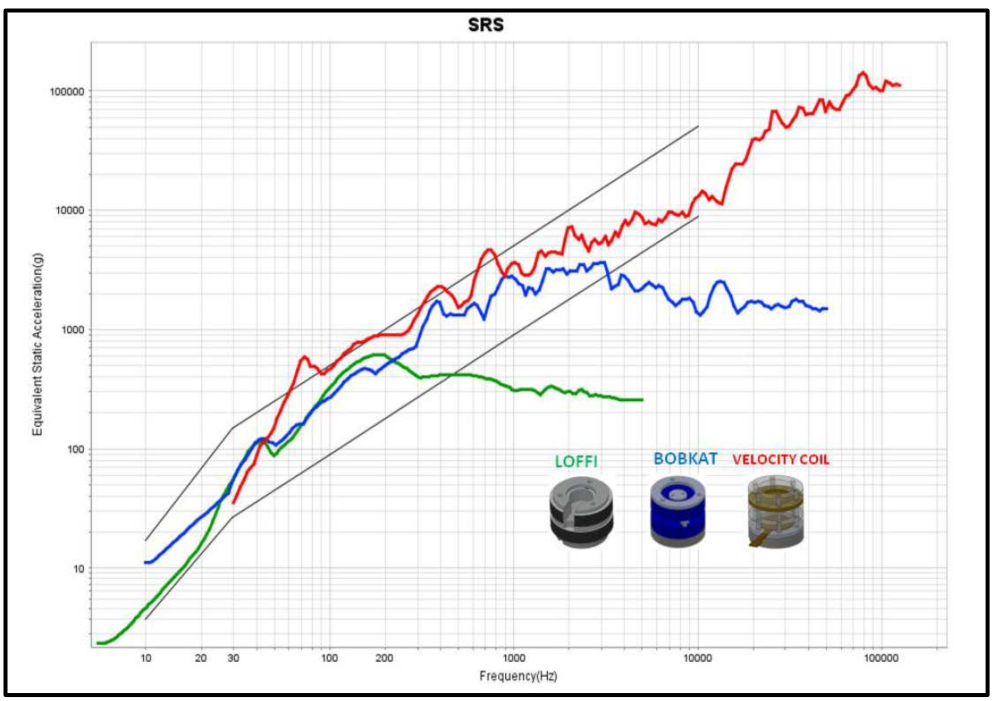

Figure 28. Figure 522.2-2 from Method 522.2 of MIL-STD-810G CN1

c. There are some measurement requirements within the realm of ballistic shock that will not subject the accelerometer to mechanical inputs above 10 kHz. An example of one such measurement is the response of a “stroking” seat. These seats use dampening systems to dramatically decrease the loading to vehicle occupants to help ensure their survivability from a UBB event. They are decoupled and far enough removed from the source of the ballistic event that the mechanical input will likely never exceed the operating bandwidth of the accelerometer. If sound engineering judgement, modeling results and/or historical data can warrant this claim, it is not necessary to include a mechanical filter and the accelerometer can be directly mounted, using the manufacturer’s recommended specifications. If this is found to be the case, further testing to validate the accelerometer is not required.

d. For measurement requirements within the realm of ballistic shock that will subject the accelerometer to mechanical inputs above 10 kHz, it is necessary to test the accelerometer and mechanical filter together to determine the total system response to full-spectrum ballistic shock.

e. Again referencing Method 522.2; *“Actual shock levels vary with the type of vehicle, the specific munition used, the impact location or proximity, and where on the vehicle the shock is measured.”* Though the “default” shock levels listed in Method 522.2 are not necessarily the shock level indicative to every ballistic shock event, they serve as a good starting point when no field measurement results are available. These values are listed in Table 1 and plotted in a Shock Response Spectrum (SRS) shown in Figure 29.

TABLE 1. TABLE 522.2-I BALLISTIC SHOCK CHARACTERISTICS
(FROM METHOD 522.2 OF MIL-STD-810G CN1)

AVERAGE SHOCK				WORST CASE SHOCK		
Maximum Resonant Frequency (Hz)[b]	Peak Displacement (mm)	Peak Velocity (m/s)	Peak Value of SRS[a] (g’s)	Peak Displacement (mm)	Peak Velocity (m/s)	Peak Value of SRS[a] (g’s)
10	15	1.0	60	42	2.8	17
29.5	15	3.0	52.5	42	8.5	148
100	15	3.0	178	42	8.5	502
1,000	15	3.0	1,780	42	8.5	5,020
10,000	15	3.0	17,800	42	8.5	50,200
100,000	15	3.0	178,000	42	8.5	502,000

[a] SRS is Equivalent Static Acceleration for a damping ratio equal to 5 percent of critical.
[b] Tests involving all frequencies from 10 Hz to maximum frequency indicated.

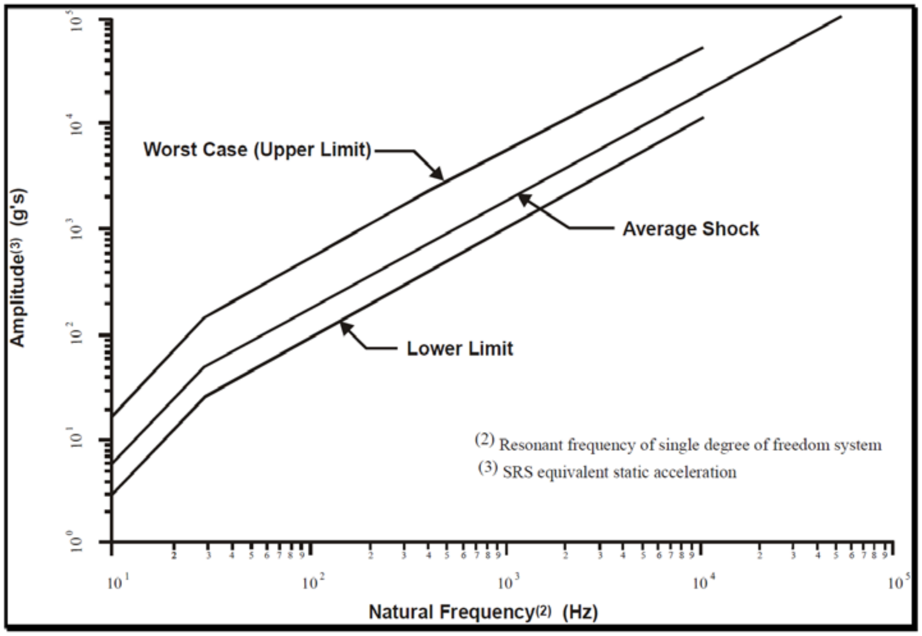

Figure 29. Figure 522.2-1 from Method 522.2 of MIL-STD-810G CN1.

f. Full-spectrum (0-100,000 Hz) testing can be completed using any mechanical shock simulator, so long as it is capable of producing the shock levels specified in Table 1. For the example provided in Table 2, the smack bar as originally described in Paragraph 4.3 will be used. To begin, the LDV should be positioned overhead as displayed in Figure 14, and a series of preliminary tests should be conducted to determine the setup parameters required to achieve an input that falls within the specified bounds. Method 522.2 states that *"for a test shock to be considered an acceptable simulation of the requirement, 90 percent of the points in the region from 10 Hz to 10 kHz must fall within the bounds listed in Table 522.2-II"*.

TABLE 2. TABLE 522.2-II SRS FUNCTION FOR SHOCK
(FROM METHOD 522.2 OF MIL-STD-810G CN1)

BOUNDARY	NATURAL FREQUENCY	
	From 10 to 29.5 Hz	From 29.5 to 10 kHz
Upper Bound	SRS = 0.17020f^2	SRS = 5.020f
Average Shock (default)	SRS = 0.06033f^2	SRS = 1.780f
Lower Bound	SRS = 0.03026f^2	SRS = 0.8927f

g. An example of a velocity-time history as measured from the LDV from a specified level event (produced from the smack bar) is shown in Figure 30.

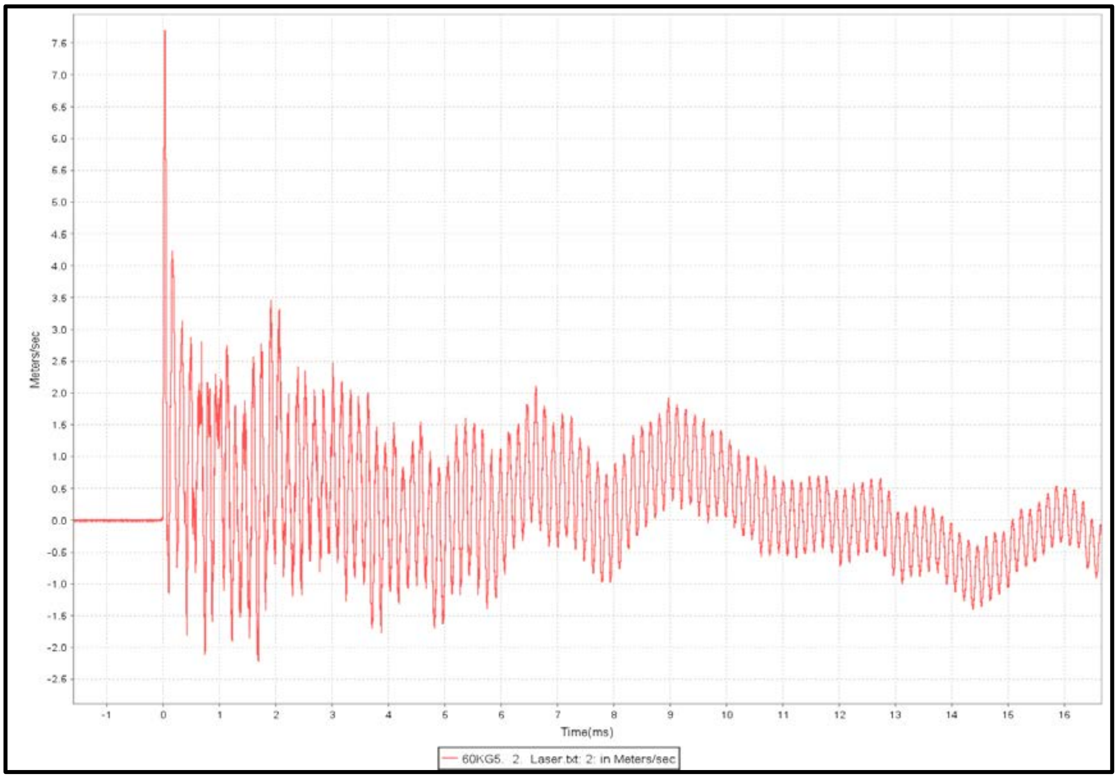

Figure 30. Velocity-time history from Method 522.2 Specified Level Event.

h. It may be necessary to remove artifacts form the velocity-time history before continuing. Intermittent loss of signal (drop out) from the LDV is common and can be a result of dust particulates entering the laser beam during the test. An example of dropout is shown in the velocity-time history presented in Figure 31. Signal dropout is distinguished as momentary high-frequency spikes riding on the velocity trace, most notably at about 105 msec. The zoomed portion of the record shows (in red) the fit used to eliminate the spike from the dataset.

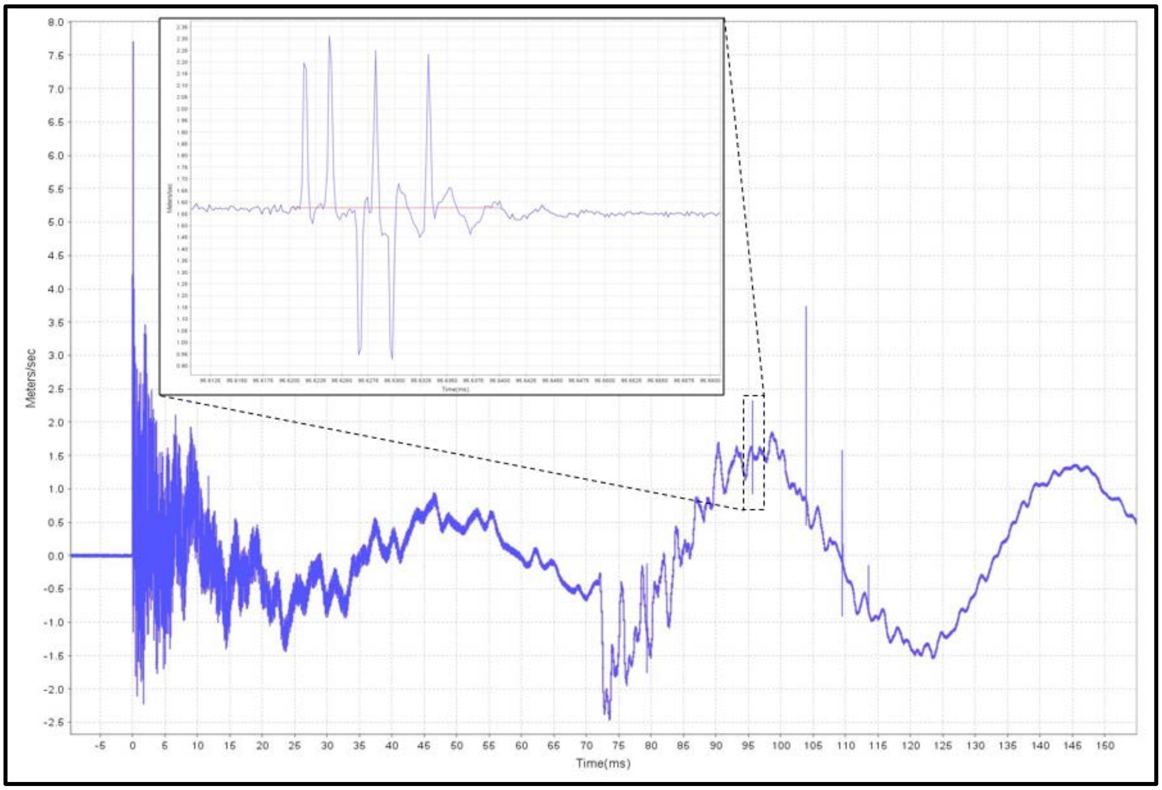

Figure 31. Typical drop out of LDV signal and correction technique.

i. The resulting SRS of the corrupted velocity signal (containing LDV dropout) and the corrected velocity signal (LDV dropout removed) is shown in Figure 32. Notice that the contaminated LDV velocity creates erroneous SRS results at frequencies above 10 kHz. Although 10 kHz is the limit of the shock requirement, the SRS is carried to 1,000 kHz to show the full-content of the recorded signal. It is important to remember that the content present at higher-frequencies is what is damaging to high-*g* MEMS accelerometers. The corrected LDV velocity signal is used for the remainder of the analysis.

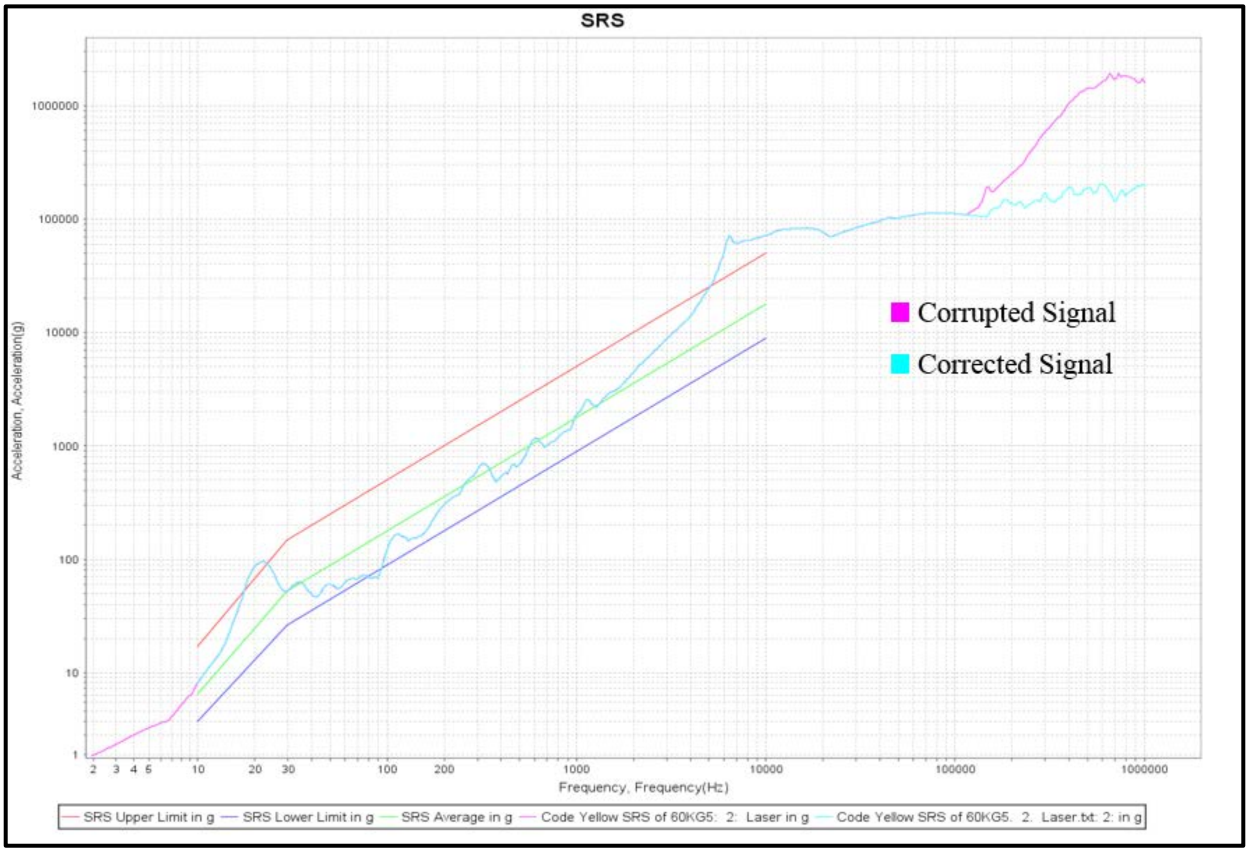

Figure 32. SRS of velocity-time record

j. Once the appropriate test levels have been determined, the accelerometer to be evaluated should be properly installed in the mechanical filter and attached to the smack bar. A diagram of the mechanical filter used in this example is shown in Figure 33. The filter shown incorporates two viscoelastic isolators on the top and bottom of the accelerometer.

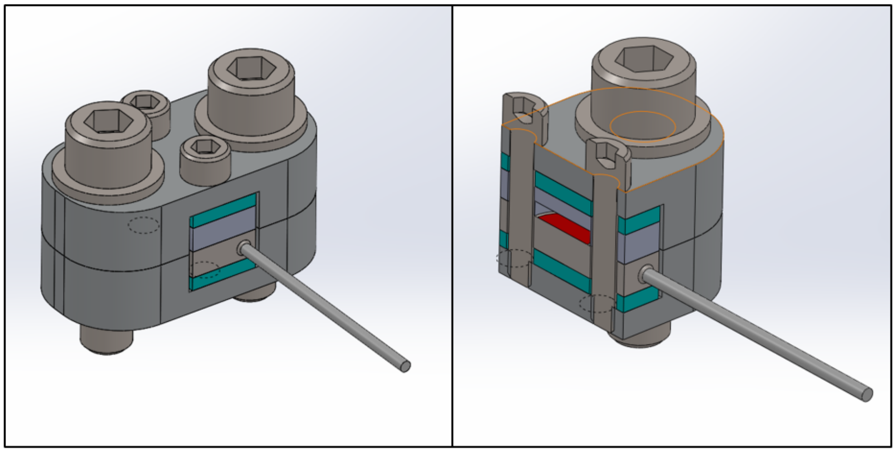

Figure 33. Mechanical filter for high-*g* MEMS accelerometer.

k. Using the identified parameters, a series of tests should be conducted until it is confirmed the UUT (mechanical filter and accelerometer) has been subjected to a specified level event. Minor tuning of test parameters may be required due to the slight increase in mass of the UUT. A typical acceleration output from the UUT in Figure 33 subjected to the input presented in Figure 30 and Figure 32 is shown in Figure 34. The maximum acceleration of the event is just below the 60,000 *g* full-scale range of the accelerometer. Traces of the accelerometer's 400 kHz resonant frequency can be noticed after the initial acceleration pulse. As demonstrated earlier in the TOP, the Q-factor of the accelerometer is so high that resonance is partially excited even with the use of a mechanical filter designed to prevent its occurrence, highlighting the necessity of the filter in this environment.

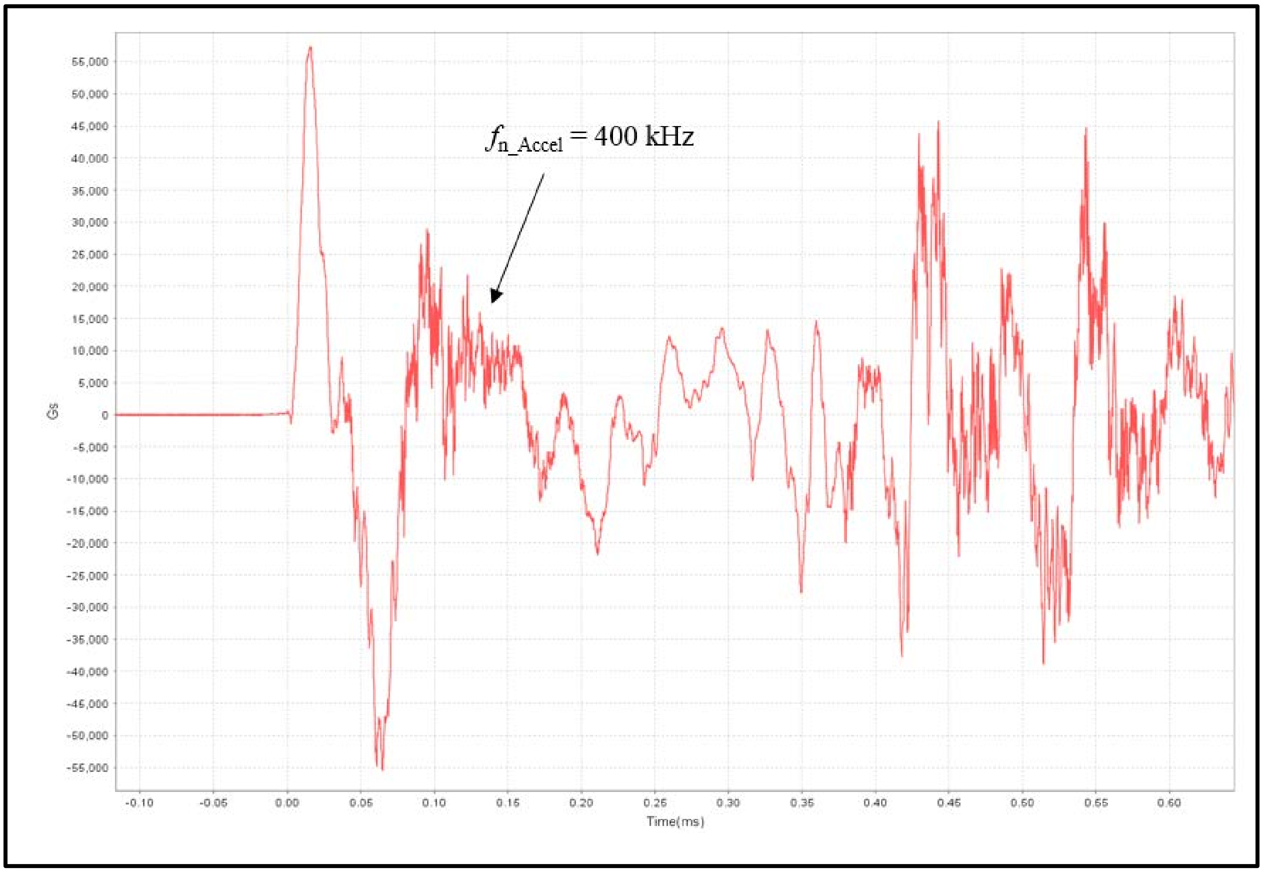

Figure 34. UUT output from full-spectrum event.

l. Once full-spectrum testing is complete, the methods described in Paragraph 4.3 should be used to determine the auto-spectrum, FRF, and coherence between the UUT and the LDV. A typical auto-spectra from the LDV and UUT subjected to a full-spectrum event can be seen in Figure 35. The resonant frequency of the mechanical filter can be seen as the amplification between 20 and 30 kHz (red-trace), after which the filter acts as intended and begins to reduce

the input measured by the LDV. At the resonant frequency of the accelerometer (~400 kHz) the mechanical filter has provided nearly 20 dB of attenuation from the mechanical input.

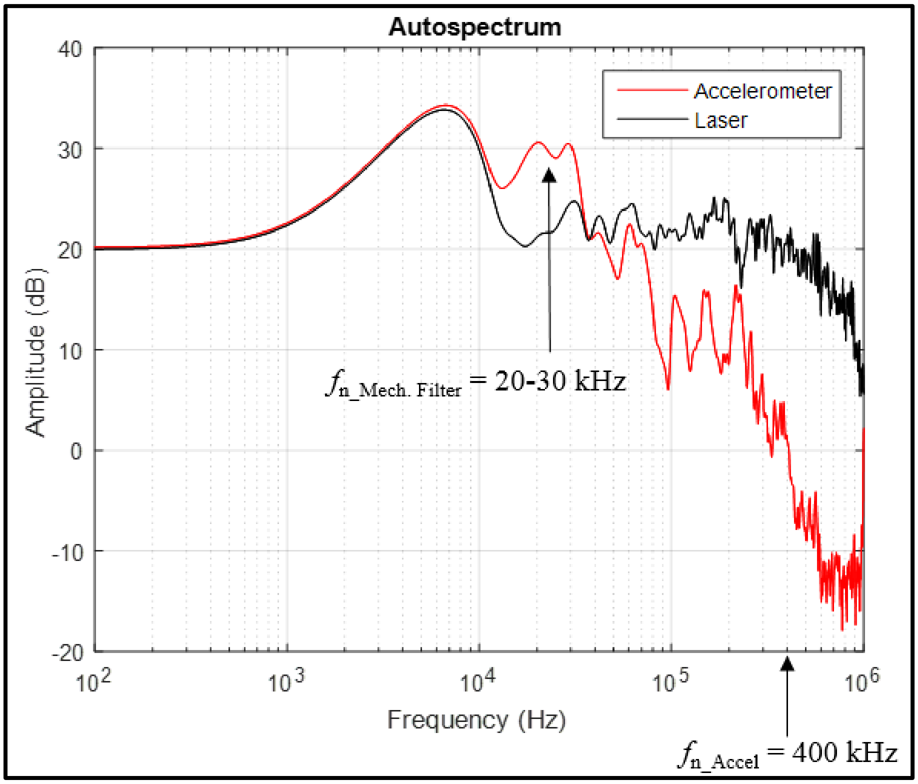

Figure 35. LDV and UUT auto-spectrum from full-spectrum smack bar test.

m. The FRF corresponding to the auto-spectra in Figure 35 is shown in Figure 36. It can be seen that the FRF is flat to within ± 10% (red-lines) in the operating region of the UUT or 100 - 10,000 Hz. Amplification from resonance of the mechanical filter is approximately 5 dB at 20 kHz. Coherence between the LDV and UUT is shown in Figure 37, and remains between 0.9 and 1.0 in the operating region.

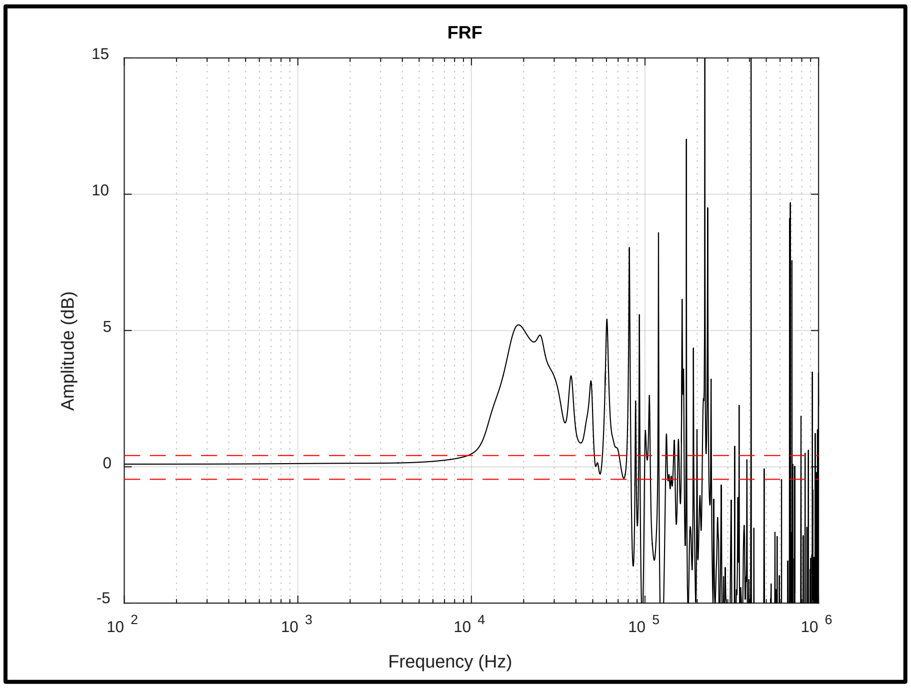

Figure 36. FRF of UUT from full-spectrum smack bar test.

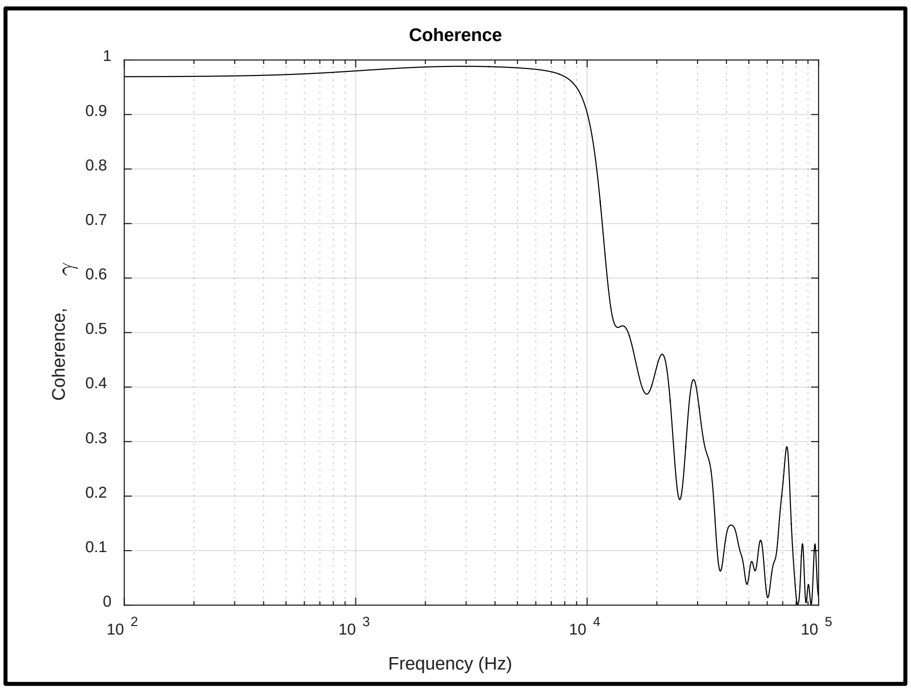

Figure 37. Coherence of UUT from full-spectrum smack bar test.

n. Raw acceleration responses (500 kHz bandwidth) from the UUT and the LDV are plotted in Figure 38. The red-trace is the differentiated velocity signal from the LDV and the blue-trace is the response from the UUT. There is an amplitude and phase difference between the two signals, as this was recorded outside the "useful frequency" range of the UUT. The filtered response (10 kHz 4th order LP Butterworth) is plotted in Figure 39, showing the relative agreement between the two signals when filtered to the operating limits of the UUT.

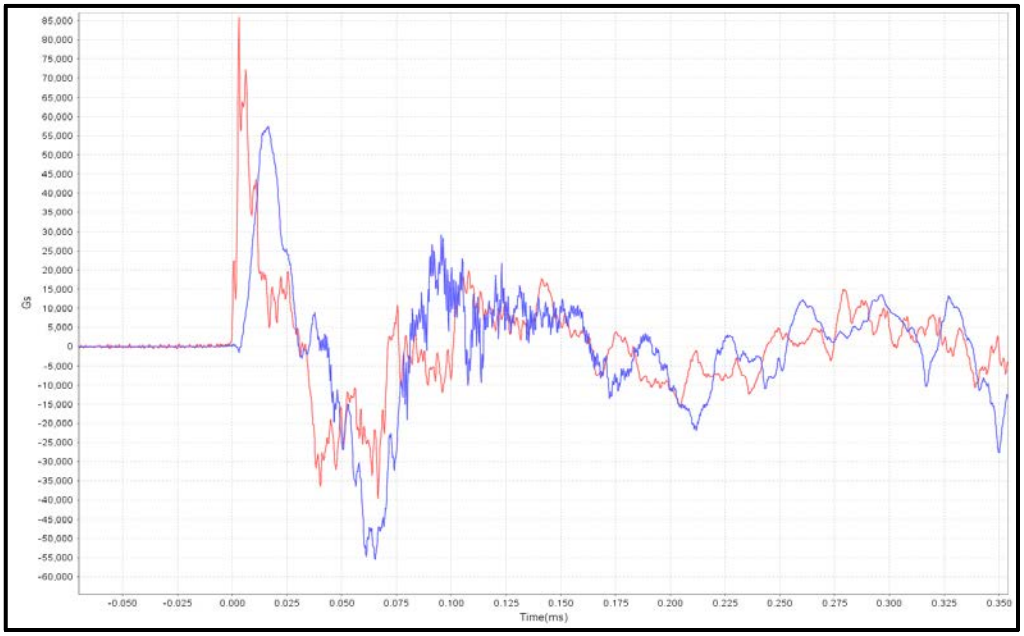

Figure 38. Raw acceleration-time history of LDV and UUT.

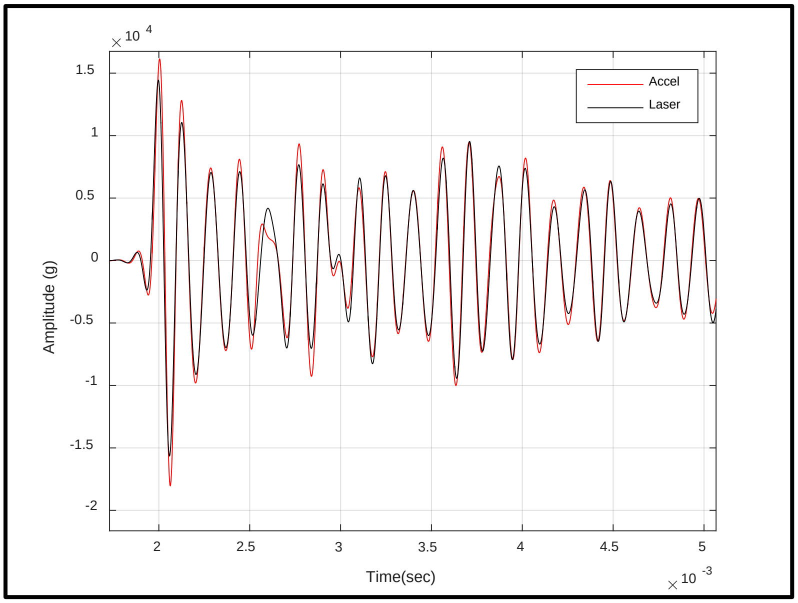

Figure 39. Filtered response of LDV and UUT.

4.7 Low-Frequency Testing.

a. Though not specified in MIL-STD-810G CN1 for ballistic shock, there is content below 10 Hz that is of interest during LFT&E to assess vehicle motion subsequent to the detonation (i.e., jump height). For the low-frequency band of interest, it is important to remember that although the selected transducer will only be used to measure 1-50 Hz content, it will still be subjected to the total shock profile. Typically, a high-output low-sensitivity accelerometer is used in this region to discern low-level accelerations experienced during bulk motion. These gauges typically have a measuring range of less than 2000 *g* and are easily saturated by the mechanical input present in a full-spectrum event. As a result, mechanical filters are often implemented to reduce the mechanical input exceeding the range of interest to ensure accelerometer survival. As an example, two varieties of the Low Frequency Foam Isolated (LOFFI) mechanical filter are pictured in Figure 40. The LOFI utilizes layers of open-cell foam rubber and a mass (to which the gauge is attached) to create a Single-Degree of Freedom mass spring damper assembly that can be tuned to desired characteristics by varying the mass and springs.

Figure 40. Low-frequency mechanical filters.

b. To test UUT's designed to have a useful frequency response below 50 Hz, it is beneficial to extend the displacement capabilities of the mechanical shock simulator. One such method to accomplish this is with the use of the "flyaway" apparatus shown in Figure 41. The flyaway attachment for the smack bar was designed to test for low frequency performance and ballistic trajectory accuracy. The setup is similar to the smack bar machine with the exception that the impacted surface (called the flyaway disc) and the UUT are unconstrained in the vertical direction, and are free to travel after impact from the air gun fired projectile. Total free vertical travel is limited to 30 inches, but this allows enough time to measure the response from the UUT during freefall.

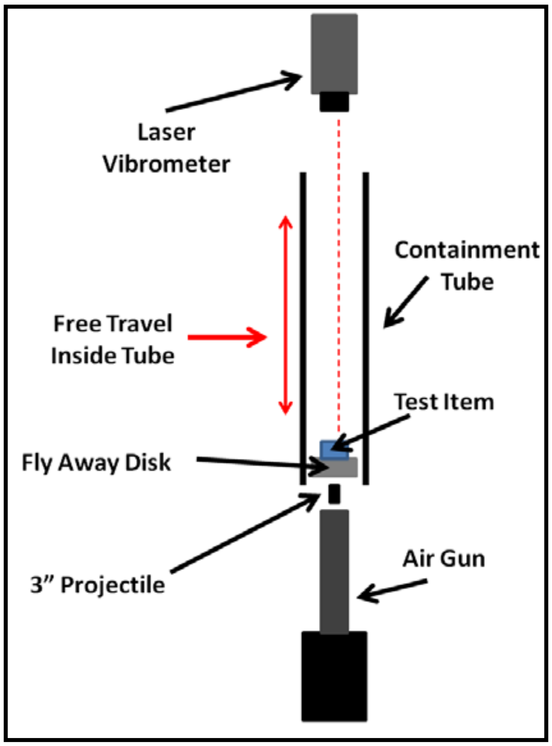

Figure 41. Conceptual schematic of Fly-Away Test Device.

4.8 <u>Explosively Driven Testing</u>.

a. The final validation should come in the form of an explosively-driven test aimed at driving the UUT to the upper end of the Ballistic Shock Spectrum. It can prove difficult in a laboratory setting to produce high enough inputs that match those experienced in an actual ballistic shock event. Typically, resources limit the ability to conduct explosively-driven testing designed solely for the evaluation of accelerometers. The large majority of initial real-world Ballistic Shock testing of accelerometers comes from "piggy-backing" on other test programs. This route generally doesn't allow for the inclusion of reference instrumentation to assess the performance of the accelerometer. However, if proper laboratory evaluations have been

completed, enough background information should be available to make a reasonable assessment of the accelerometer's performance based on its output alone.

b. Ideally, a test apparatus should be designed that mimics the response of an actual system to undergo LFT&E. The test rig shown in Figure 42 was designed to simulate a tactical vehicle floor during UBB loading, and was intended to provide a realistic loading scenario with high frequency content specifically for accelerometer and mechanical filter evaluation. Reference "truth data" should be collected to allow for evaluation of accelerometer performance during testing. Reference data should have known uncertainty and error margins. Examples of "truth data" include LDV, PDV, and Digital Image Correlation through the use of high-speed photography. The SRS, calculated from LDV response, of the floor plate in Figure 42 resulting from an explosively driven test is shown in Figure 43.

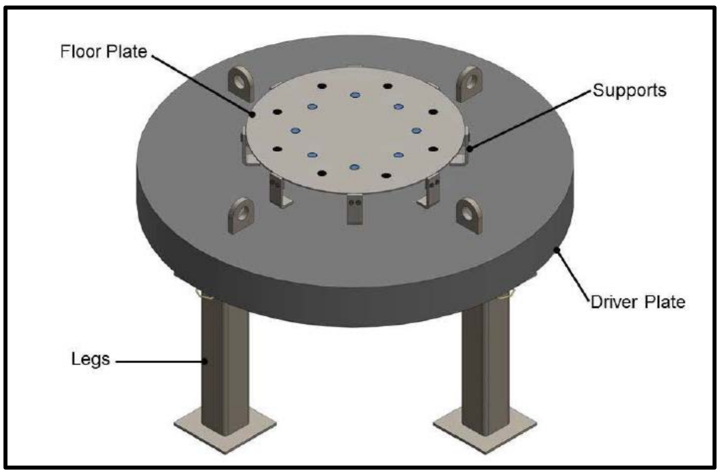

Figure 42. Explosively-driven test rig.

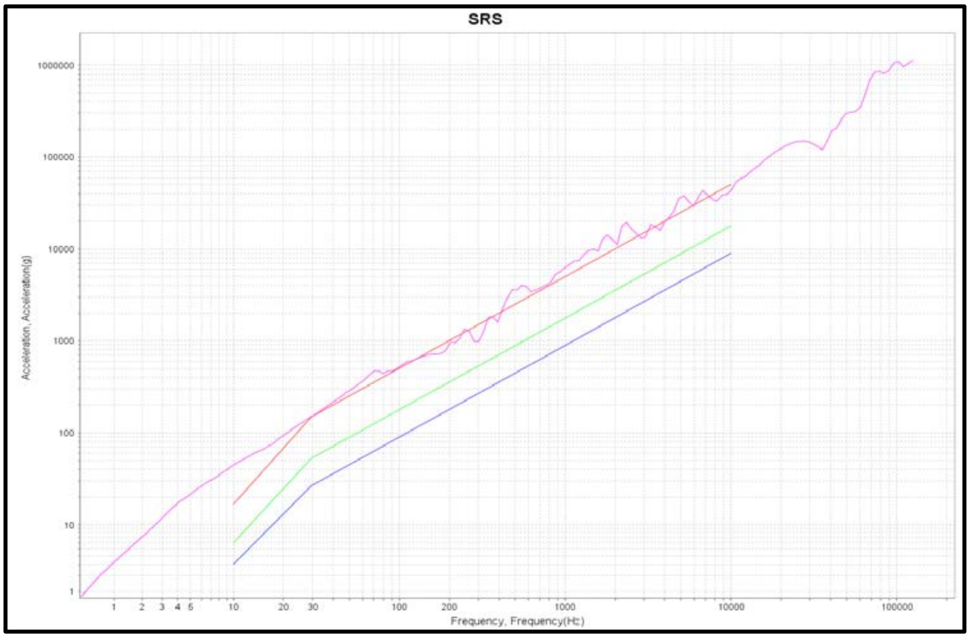

Figure 43. SRS of explosively-driven test rig response.

c. Evaluations of accelerometer and mechanical filter performance, compared to the selected reference data, should be conducted to determine the operating performance of the UUT in the ballistic shock environment.

5. DATA REQUIRED.

The data required for the validation of ballistic shock transducers in listed in the Section 4 sub paragraphs of this TOP.

6. PRESENTATION OF DATA.

Data can be presented in either a tabular or graphic format. The format to be used should be decided prior to any testing, with a mutual agreement between the tester and customer. Examples of data graphs and plot are provided throughout Section 4 of this TOP. Specific examples can be found in Figures 13, 15, 18, 25, 32, and 34.

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APPENDIX A. MILITARY STANDARD 810G CHANGE NOTICE 1, METHOD 522.2, SECTION 4.4.2.

The information in this appendix is verbatim with the procedures in Section 4.4.2, Method 522.2 Ballistic Shock, of MIL-STD-810G CN1. To preserve consistency between the two documents, paragraph and figure numbering in this appendix are the same as those in MIL-STD-810G CN1.

4.4.2 Data Acquisition Instrumentation.

4.4.2.1 Filtering and Frequency Response.

The data recording instrumentation shall have flat frequency response to at least 100 kHz for at least one channel at each measurement location. Attenuation of 3 dB at 100 kHz is acceptable. The digitizing rate must be at least 2.5 times the filtering frequency. Note that when measurements of peak amplitude are used to qualify the shock level, a sample rate of at least 10 times the filtering frequency (1 million samples per second) is required. Additional, lower frequency measurement channels, at the same location may be used for lower frequency response measurements. It is imperative that a responsibly designed system to reject aliasing is employed. Analog anti-alias filters must be in place before the digitizer. The selected anti-alias filtering must have an attenuation of 50 dB or greater, and a pass band flatness within one dB across the frequency bandwidth of interest for the measurement (see Figure 522.2- 3). Subsequent resampling (e.g., for purposes of decimation), must be in accordance with standard practices and consistent with the analog anti-alias configuration (e.g., digital anti-alias filters must be in place before subsequent decimations).

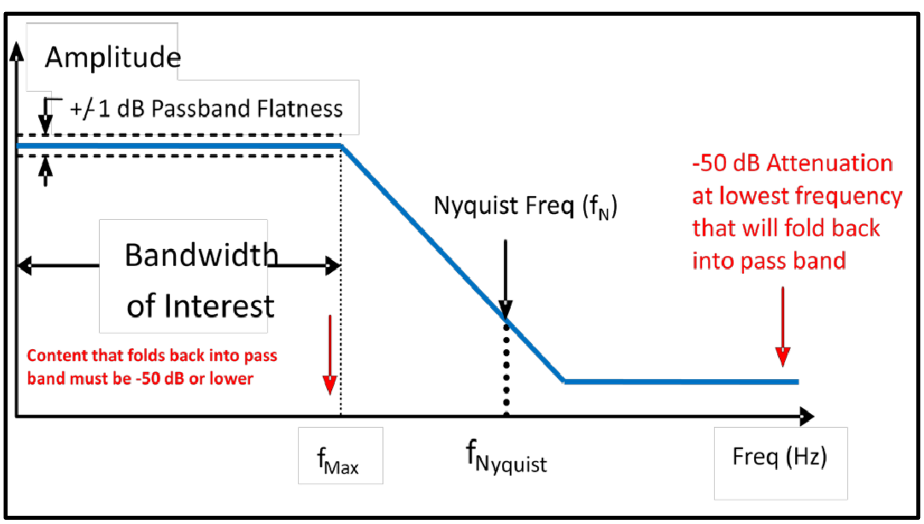

Figure 522.2-3. Filter attenuation (conceptual, not filter specific).

APPENDIX A. MILITARY STANDARD 810G CHANGE NOTICE 1, METHOD 522.2, SECTION 4.4.2.

The end to end alias rejection of the final discretized output must be shown to meet the requirements in Figure 522.2-3. The anti-alias characteristics must provide attenuation of 50 dB or greater for frequencies that will fold back into the passband. Spectral data including SRS plots may only be presented for frequencies within the passband (between 0 and fmax). However, this restriction is not to constrain digital data validation procedures that require assessment of digitally acquired data to the Nyquist frequency (either for the initial analog to digital converter or subsequent resampled sequences).

Verification of alias rejection should start by establishing the dynamic range within the pass band in terms of the signal to noise ratio (SNR). The 20log10 ( ) *SNR = VFullScale VNoisefloor* must be ≥ 60 dB. Once sufficient SNR is verified, establishing the alias rejection characteristics may be determined using an input sine wave with a magnitude of 0.5 * full scale range and at the lowest frequency range that can impinge (i.e., be aliased into *f*max), and then confirming (using the Institute of Electrical and Electronics Engineers (IEEE) 1057[12] sine wave test procedure or through inspection of the time domain data) that the alias rejection is sufficient at this frequency. If the 1 million sample/second digitizing rate is used, for example, then fNyquist = 500 kHz. Theory says that if a signal above the Nyquist Ratio is present, it will “fold over” into a frequency below the Nyquist ratio. The equation is:

Fa = absolute value [(Fs*n)-F], where:

Fa = frequency of “alias”
F = frequency of input signal
Fs = sample rate
N = integer number of sample rate (Fs) closest to input signal frequency (F)

Hence, the lowest frequency range that can fold back into the 100 kHz passband is from 900 kHz to 1,100 kHz = 0.9 to 1.1 MHz. It should be noted that Sigma Delta (SD) digitizers “oversample” internally at a rate several times faster than the output data rate. Analog anti-alias filtering for SD digitizers may be used at the Nyquist rate for the internal sample rate. For example, if a 1 million sample/second SD digitizer samples internally at 8 million samples/second, then the internal Nyquist frequency is 4 MHz, hence the analog anti-alias filter should remove content above 4 MHz that can fold back into the 100 kHz pass band (7.9 MHz to 8.1 MHz and similar bands that are higher in frequency).

Figure 522.2-4 illustrates sampling frequencies, Nyquist frequencies, and frequency bands that can fold back into the bandwidth of interest for both conventional (“Successive Approximation”) digitizers and over sampling digitizers, such as the Sigma Delta digitizer.

APPENDIX A. MILITARY STANDARD 810G CHANGE NOTICE 1, METHOD 522.2, SECTION 4.4.2.

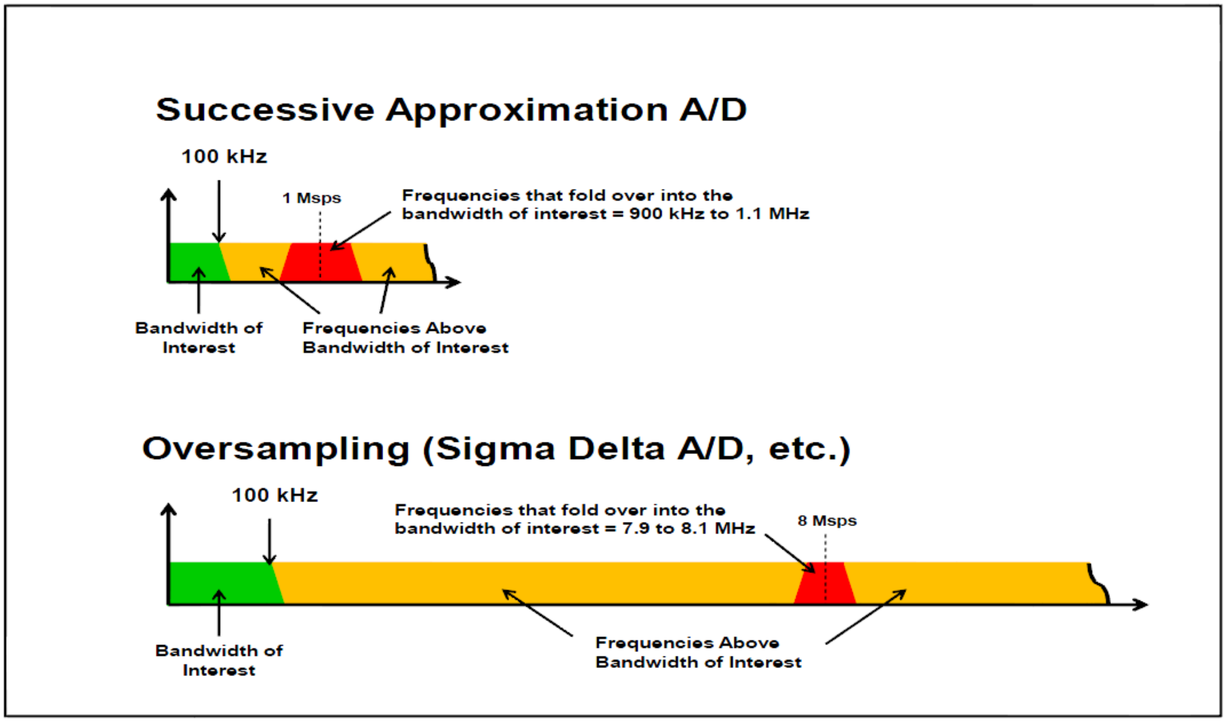

Figure 522.2-4. Illustration of sampling rates and out of band “fold over” frequencies for data acquisition systems.

4.4.2.2 Slew Rate.

To prevent distortion caused by spurious electrical noise, the data recording instrumentation shall be capable of recording a signal of one half full scale voltage in 1 microsecond without slew rate distortion. For example, if a system is capable of + 10 volts full scale = 20 volt peak-to-peak, then a slew rate of 10 volt/µsecond is required.

4.4.2.3 Headroom.

Undamped PE and Micro Electro-Mechanical System (MEMS) accelerometers are known to produce very high output signals at resonance (up to 100 times higher than the actual mechanical input). For Procedures I Ballistic Hull and Turret, II Large Scale Ballistic Shock Simulator, III Limited Spectrum, Light Weight Shock Machine, and IV Limited Spectrum, Mechanical Shock Simulator, there is serious risk of significant “Out of Band Energy” being generated by undamped accelerometers. This high frequency “Out of Band Energy” is capable of causing distortion in the data recording electronics. Precautions must be

APPENDIX A. MILITARY STANDARD 810G CHANGE NOTICE 1, METHOD 522.2, SECTION 4.4.2.

taken (and documented) to insure that “Out of Band Energy” signals, produced by undamped accelerometers, do not distort “In Band” measurements, due to inadvertent clipping at various amplification stages of the analog signal conditioning. The following alternatives are examples of acceptable precautions:

a. Use of critically damped transducers (which do not produce significant “Out of Band Energy”).

b. Use of long multi-conductor cables is not desirable, but is often unavoidable. Long cables can significantly attenuate the “Out of Band Energy” signals. If, for example, cable attenuation is shown to be -34 db (a factor of 50X) or more, at the resonant frequency of the undamped accelerometer, then the cable alone serves as acceptable protection from “Out of Band Energy”.

c. Use of an analog detector at each stage of amplification, to insure that no signal “clipping” occurs prior to filtering, serves as acceptable documentation as to where “Out of Band Energy” distortion did, or did not occur.

d. Setting the full scale recording range to a factor of roughly 25X above the expected signal level (i.e., a “Headroom” of 25X) serves as acceptable protection from internal clipping due to “Out of Band Energy”. If the expected level was 2,000 *g* for example, the full scale range would be set to 50,000 *g*. Hence, a 50,000 *g* “Out of Band Energy” signal could be accommodated without clipping. Unfortunately, the expected “In Band” signal level would only use 4% of the full scale capability of the recorder, compromising signal fidelity. Note that use of “Post Filter Gain” (gain applied after the anti-alias filter has removed the “Out of Band Energy”), reduces the amount of headroom required. In the previous example, the pre-filter gain would still be set to provide a range of 50,000 *g*, but additional gain after the filter could amplify the signal before digitization, thereby increasing fidelity. The headroom of the post-filter gain would depend on knowledge of the expected in-band signal and fidelity requirements. For situations where the expected level is not well understood a post-filter gain overhead of 10X is recommended, or 20,000 *g* in the example case.

APPENDIX B. GLOSSARY.

Term	Definition
Accelerometer	An instrument for measuring acceleration.
Cutoff frequency	A boundary in a system's frequency response at which energy flowing through the system begins to be reduced (attenuated or reflected) rather than passing through.
Piezoelectric	A piezoelectric accelerometer is an accelerometer that employs the piezoelectric effect of certain materials to generate an electrical output proportional to applied acceleration.
Piezoresistive	A piezoresistive accelerometer is an accelerometer that convert mechanical energy from acceleration into proportionate levels of resistance.
Sampling rate	The rate at which an Analog to Digital converter converts an analog signal into a stream of digital numbers, each representing the analog signal's amplitude at a moment in time expressed in Hz or kHz.

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APPENDIX C. ABBREVIATIONS.

μs	microsecond
μV/με	microvolt per microstrain
ATC	U.S. Army Aberdeen Test Center
dB	decibel
DC	direct current
DVM	digital volt meter
FFT	Fast Fourier Transform
FRF	Frequency Response Function
ft	foot/feet
g	acceleration 1 g = 9.81 m/s^2
Hz	Hertz
IEEE	Institute of Electrical and Electronics Engineers
IOP	Internal Operating Procedure
kHz	Kilohertz
lb	pound
LDV	Laser Doppler Vibrometer
LFT&E	Live Fire Test and Evaluation
LOFFI	low frequency foam isolated
m/s or m/sec	velocity in meters per second
MEMS	Micro Electrical Mechanical System
MHz	Megahertz
MIL-STD	Military Standard
mm	millimeter
ms or msec	millisecond (0.001 seconds)
mV	millivolt
PDV	Photon Doppler Velocimeter
PE	piezoelectric
PR	piezoresistive

APPENDIX C. ABBREVIATIONS.

SD	Sigma Delta
SNR	signal to noise ratio
SRS	Shock Response Spectrum
TOP	Test Operations Procedure
UBB	under body blast
UUT	Unit Under Test
V	volt
VHSD	VISION High Speed Digitizer
VISION	Versatile Information Systems Integrated On-Line
ZMO	Zero Measurand Output

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b. B. T. Hepner, M. Christopher, and S. W. Walton, "Improved Mid-Frequency Measurement of Ballistic Shock", *81st Shock and Vibration Symposium, Shock & Vibration Exchange*, 2010.

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APPENDIX E. APPROVAL AUTHORITY.

CSTE-TM 5 June 2017

MEMORANDUM FOR

Commanders, All Test Centers
Technical Directors, All Test Centers
Directors, U.S. Army Evaluation Center
Commander, U.S. Army Operational Test Command

SUBJECT: Test Operations Procedure (TOP) 01-1-070 Initial Validation of Ballistic Shock Transducers, Approved for Publication

1. TOP 01-1-070 Initial Validation of Ballistic Shock Transducers, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency. The scope of the document is as follows:

The objective of this TOP is to describe various methods and instrumentation used in the initial validation of accelerometers to be used in both Ballistic Shock testing and crew/vehicle survivability Live Fire Test and Evaluation.

2. This document is approved for publication and will be posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 2202 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Policy and Standardization Division (CSTE-TM), U.S. Army Test and Evaluation Command, 2202 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: Ballistics Instrumentation Division (TEDT-AT-SLB), U.S. Army Aberdeen Test Center, 400 Colleran Road, Aberdeen Proving Ground, Maryland 21005 Additional copies can be requested through the following website: http://www.atec.army.mil/publications/topsindex.aspx, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.